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OPTIMIZATION OF WASTES TREATMENT WITH REFERENCE TO BIOGAS AND PROTEIN RECOVERY

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Detailed technological and economic evaluation of the presently used treatment processes for the dilute wastewaters from hog farms, with capacity exceeding 10 thousand heads, is presented. The research part of the project was aimed at optimization of the unit process and whole treatment trains selection, rather than unit process operational parameters. The results indicate the need for diametrical shift in research emphasis in animal wastes, towards high-rate, short detention time anaerobic unit process combined with high-rate aerobic secondary treatment and anaerobic-aerobic polishing treatment. Several full technological treatment trains were evaluated and compared, from the standpoint of treatment efficiency, level of recovery, ease of maintenance and economic efficiency indices. The economic analysis has proved that the application of these new treatment trains can make industrial scale farming more profitable with the increase of the size of the farm. The technology proposed in the project will show increase of the economic efficiency, when compared to conventional systems, with the increase of power costs, due to biogas recovery and incorporation of sludge treatment subsystem in the overall treatment-recovery train. Although the report is confined to swine wastes, the results are applicable to other concentrated effluents from agricultural industry.

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FOREWORD

EPA is charged by Congress to protect the Nation's land, air and water systems. Under a mandate of national environmental laws focused on air and water quality, solid waste management and the control of toxic substances, pesticides, noise, and radiation, the Agency strives to formulate and implement actions which lead to a compatible balance between human activities and the ability of natural systems to support and nurture life. In partial response to these mandates, the Robert S. Kerr Environmental Research Laboratory, Ada, Oklahoma, is charged with the mission to manage research programs to investigate the nature, transport, fate, and management of pollutants in ground water and to develop and demonstrate technologies for treating wastewaters with soils and other natural systems; for controlling pollution from irrigated crop and animal production agricultural activities; for controlling pollution from petroleum refining and petrochemical industries; and for managing pollution resulting from combinations of industrial/industrial and industrial/municipal wastewaters.

This project was initiated to evaluate the presently used treatment systems for wastes from large swine farms in Poland and to optimize the system with the addition of a subsystem to produce biogas and to recover protein. The project provided an opportunity to study large, full-scale plants that do not now exist in this country. The results indicate that biogas can be produced successfully from a much more dilute waste than had been previously reported. It also optimized the systems both from a technological and economic standpoint. The information will be very useful in this country as urban pressure requires more complex treatment of animal wastes in the future.

Clinton W. Hall

Clinton W. Hall, Director
Robert S. Kerr Environmental
Research Laboratory

ABSTRACT

Detailed technological and economic evaluation of the presently used treatment processes for the dilute wastewaters from hog farms, with capacity exceeding 10 thousand heads, is presented. The present systems of treatment for stream disposal encompass sophisticated multi-stage chemical-biological treatment with high unit costs due to consumption of power, oil and chemicals.

The research part of the project was aimed at optimization of the unit process and whole treatment trains selection, rather than unit process operational parameters. The unit processes investigated in laboratory and pilot scale included: sedimentation, coagulation, activated sludge as a roughing and as a polishing unit, algal-bacterial (oxidation) polishing ponds, anaerobic digestion in flow-through and contact reactors with suspended microorganisms and in anaerobic biofilters, anaerobic ponds, aerated lagoons, and yeast generation, as a method of treatment and protein recovery.

The results indicate the need for diametrical shift in research emphasis in animal wastes, towards high-rate, short detention time anaerobic unit process combined with high-rate aerobic secondary treatment and anaerobic-aerobic polishing treatment. Several full technological treatment trains were evaluated and compared, from the standpoint of treatment efficiency, level of recovery, ease of maintenance and economic efficiency indices. The systems recommended comprised of anaerobic biofiltration or contact digestion followed by anaerobic biofiltration, anaerobic biofiltration and reaeration, with anaerobic sludge digestion as a separate sludge train or incorporated in the wastewater treatment train. The economic analysis has proved that the application of these new treatment trains can make industrial scale farming more profitable with the increase of the size of the farm. This is contrary to the presently observed trend toward limiting the construction of

large farms, due to the environmental constraints. The discouraging experiences stem from the application of either conventional wastewater treatment technology to these concentrated effluents, or application of agricultural utilization practices as used for concentrated manures from smaller farms.

The technology proposed in the project will show increase of the economic efficiency, when compared to conventional systems, with the increase of power costs, due to biogas recovery and incorporation of sludge treatment subsystem in the overall treatment-recovery train. Although the report is confined to swine wastes, the results are applicable to other concentrated effluents from agricultural industry.

This project has been conducted within the frame of a bilaterial financial arrangement, the Maria Sklodowska-Curie Fund for cooperative programs between Poland and the United States. The work has been accomplished between October 1, 1976 and November 30, 1980, by the Research Institute on Environmental Development - Wroclaw Division and U. S. Environmental Protection Agency - Robert S. Kerr Environmental Research Laboratory in Ada, Oklahoma.

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LIST OF ABBREVIATIONS AND SYMBOLS

AA -- amino acid
AB -- anaerobic biofilter
AD -- anaerobic digestion
ANBIOF -- anaerobic biofilter
ANCONT -- anaerobic contact digester with sludge recycle
ANFLOW -- anaerobic flow-through digester without sludge recycle
AL -- area loading (g O_2/m^2d)
AS -- activated sludge
BOD -- biochemical oxygen demand
BVS -- biodegradable volatile solids
CMR --
CNP --
COD -- chemical oxygen demand
CTP -- combined treatment plant
D -- coagulant dose (mg/dm^3)
DC -- direct costs
DI -- digestion index
DM -- dry matter (synonym of TS)
DO -- dissolved oxygen
DP -- digestible protein
DPW -- dry poultry waste
FAO -- food and agriculture
F/M -- food to microorganism ratio (kg O_2/kg MLVSS d)
GC -- general costs
GP -- gas production from reactor volume (m^3/m^3)
GP_{avg} -- total gas production expressed per day (m^3/d)
HRT -- hydraulic retention time (d)
K -- removal rates
K_s -- Michaelis constant; i.e. substrate concentration at which; $\mu = 0.5\ \mu m$
L -- organic loading of a reactor (kg/m^3d)

L_o -- load introduced (kg/d)

L_r -- load removed (kg/d)

LW -- liveweight

MISS --

MLSS -- mixed liquor suspended solids

MLVSS -- X_v (mg/dm^3)

N -- removal efficiency $(S_o - S_e)/S_o$; (%)

OM -- operation and maintenance costs

R -- nonbiodegradable fraction

RWL -- raw waste load

S_o -- influent substrate concentration (mg/dm^3)

S_e -- effluent substrate concentration (mg/dm^3)

S_{nb} -- nonbiodegradable substrate (mg/dm^3)

S_r -- $S_r = S_o - S_e$ (mg/dm^3)

SCP -- single cell protein

SGP_{avg} -- specific gas production; total volume of gas produced divided by the total load throughput (m^3/kg)

SGP_o -- specific gas production; GP_o divided by the average daily load input (m^3/kg)

SGP_r -- specific gas production based on load removal (m^3/kg)

$SGP^a_{o,r}$ -- averaged SGP from overall cu-ulative data (m^3/kg)

SOC -- soluble organic carbon

SRT -- solids retention time (d)

SS -- suspended solids

STP -- standard temperature and pressure

SVI -- sludge volume index

TF -- trickling filter

TKN -- Kjeldahl nitrogen

TOC -- total organic carbon

TOTEM -- total engery module

TP -- total protein

TS -- total solids

TSS -- total suspended solids

TTC -- dehydrogenase

TVS -- total volatile solids

VSS -- volatile suspended solids

X_a -- assumed active (viable) cells concentration (mg/dm^3)

X_e -- VSS at the end of treatment or in the effluent (mg/dm^3)

X_v -- mixed liquor volatile suspended solids (mg/dm^3)

Y -- yield coefficient = mass of synthesized cells divided by mass of removed substrate (mg BSS/mg S_r)

b -- endogenous respiration coefficient = mass of VSS used per unit VSS in the system (mg VSS/mg VSS d) (1/d)

dm^3 -- liter

f -- subscript denoting filtered sample

nf -- subscript denoting non-filtered sample

q -- substrate removal rate; $q = S_r/X$ HRT ; (1/d)

r -- X_a/X_v smaller than unity by def. (-)

μ -- growth coefficient; $\mu = QY = \mu_m S/(K_s+S)$; (1/d)

μ_m -- maximum growth coefficient $\mu_m = q_m Y$; (1/d)

zL -- zloties, unit of Polish currency. $1 = 20 zloties

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SECTION 1

CONCLUSIONS

The project is aimed at optimizing the presently used treatment systems for dilute effluents from large piggeries, at optimization of loadings and sequence of unit processes and operations for piggery waste treatment and at placing the new waste treatment - recovery systems in the proper economic and technological perspective. The project topics could be grouped as:
a) detailed technological and economic analysis of presently used treatment systems (WTS) for dilute wastewaters for several large industrial pig farms;
b) an in-depth analysis of results of laboratory and pilot scale studies of fourteen individual unit processes for treatment of pit wastes; and c) application of obtained results to the design and economic assessment of 12 new complete WTS for two types of large pig farms with partial effluent recycle, i.e. water use 20 dm^3/hog/day and without recycle, i.e. 28 dm^3/hog/day.

It has been shown that the present highly sophisticated chemical-biological WTS can be properly operated only in case of very careful cooperation between the farm and the WTS personnel and in case of keeping the hydraulic load within the design limits. It has also been shown that these systems are vulnerable to influent variability and are highly inefficient and will cost more with the increasing costs of power, imported chemicals and oil. The recommended agricultural utilization of wastewaters is not always the desirable alternative due to even higher costs, lack of area and relatively low recovery value of nitrogen and phosphorus.

In the research part it has been shown that piggery WTS should include a sequence of high-rate processes followed by low-rate low loading processes. Chemical treatment should be replaced by plain sedimentation and/or anaerobic pretreatment. The use of activated sludge should be limited in the high-rate processes class and excluded from the low-rate processes class. The oxidation ponds as a polishing WTS should be used in combination with fish cultivation as a method of biomass harvesting.

The comparison of the various modes of anaerobic digestion proves that dilute piggery waste should be treated in high-solids retention time (SRT), low-hydraulic retnetion time (HRT) systems, and that gas production and sludge build-up decrease with increasing SRT, while the removal ratio and process stability increase. The recovery of gas is economically efficient already at the present power costs, because the anaerobic processes proposed in this project yield at the same time large removals of organics.

The recovery of single cell protein (SCP) through aerobic fermentation is found feasible, however, the present costs of protein and N, P nutrients make it an uneconomical venture from the standpoint of both the SCP production and waste treatment. Large carbon supplementation is required in order to fully utilize the nutrients contained in piggery wastes.

In all cases the alternative of combined treatment with other, nutrient lacking effluents should be investigated because the benefits are usually much higher than the cost of long-distance pressure transport systems.

It follows that the system of long detention time lagoons: anaerobic - aerated - oxidation, is a viable WTS, easy to implement and operate in rural conditions. The most efficient WTS, however, includes mesophilic anaerobic biofiltration (ANBIOF) followed by aerobic biofiltration and polishing anaerobic biofiltration. The system utilizes most of the methanogenic potential of wastes by means of a separate anaerobic sludge digestion in an ANCONT or ANFLOW type reactors, i.e. suspended growth reactors with and without sludge recycle, respectively.

The ANBIOF type reactor should always be incorporated in any treatment system as a first or second stage anaerobic digestion since it significantly improves process stability and allows (as a second stage after an ANCONT reactor) for an increase in organic loading without impairing the gas production or organics removal efficiency.

The major error in disposal of dilute piggery wastes in Europe, up to recent times, was the application of either conventional wastewater treatment technology or use of manure utilization systems applicable to concentrated wastes. Based on numerous examples of difficulties in disposal of piggery effluents, large industrial farm complexes are thought now to be economically and technologically inefficient. This project has shown that this is not necessarily so, at least from the standpoint of WTS. The accumulation of large organic loadings and relatively low volumes of wastes may be regarded as an advantage in novel, energy efficient, highly reliable gas and nutrient recovery WTS, such as demonstrated in this report.

From the standpoint of the economics of wastes treatment, piggeries with capacity smaller than 5000 head should rely on land disposal. If stream disposal is the final goal, the size of the farm should not have to be limited, since the proposed technology of anaerobic wastewater treatment and sludge disposal improves its efficiency with the increase of the farm size. Another factor improving the efficiency of the proposed systems is the decrease of fresh water use through recycle of treated wastewaters.

SECTION 2

RECOMMENDATIONS

Existing piggeries should begin the program of changes in the water distribution and sewerage systems to cut down the water use, increase the temperature and concentration of raw wastes and apply recycle with purified wastewaters for flushing purposes.

Full scale implementation of the proposed anaerobic treatment systems V and VI is needed; the design work is presently being completed. Full scale polishing oxidation ponds are being constructed. A three year period of studies should encompass various techniques of biomass growth enhancement in cold conditions such as greenhouses, mixed populations, recycle, etc. Fish cultivation should be researched as a method of biomass harvesting and biological sludge disposal.

New anaerobic treatment processes should be studied such as phase separation and selective organics removal systems to further cut down on the volumes of anaerobic fermenters. The major trend in animal waste treatment technology should be the further optimization of gas recovery and utilization of waste heat, as the rising power costs will rapidly increase the applicability of anaerobic digestion to concentrated organic effluents.

The work on yeast production should be continued with other types of yeasts that require less of the readily available carbon. Studies on continuous cultures, mixed yeasts populations need to be continued since further rises in protein prices should yield the process more economical.

Methods of direct refeeding should not be pursued as much as the methods of conversion into high protein feedstuffs. Further studies should be conducted in open rather than in close cycles, i.e. feeding other kinds of animals.

Wide technology transfer and agricultural extension programs are needed in order to show the growers, animal husbandry specialists and the agricultural industry as a whole that animal wastewaters can be treated efficiently at any level of dilution, at any volume and in any location. However, new, more sophisticated technology is required, with significant recoveries immediately available if proper liason between the producer and the sanitary engineer is established.

SECTION 3

INTRODUCTION

PROJECT AIM

The shortage of litter and the growing demand for animal protein have caused several countries to turn to industrial scale animal production husbandry. Large hog production plants in central Europe house usually from 10 to 40 thousand animals. In several instances larger farms were built, notably in Romania and USSR where the size may approach 250 thousand hogs. Taking into account the fact that a 36.5 thousand hog farm will require annually over 1.9×10^8 watthours of power, up to 18×10^6 kg of fodder and close to $3.2 \times 10^5 m^3$ of water, one realizes the magnitude of operational problems experienced with the fulfillment of environmental requirements regarding air, soil and water.

Figure 1-A illustrates the hog production trends in two countries: Holland and Poland (1, 2, 6, 7). Figure 1-B shows the increasing participation of industrial sector in hog and cattle production in Poland (3). It should be noted that industrial scale farms are responsible for much larger segment of overall pig production in such countries as East Germany-29 percent, Hungary-47 percent, Romania-60 percent, and Bulgaria-65 percent (4). Since, due to technical constraints, new farms are frequently sited in an area unfit for land disposal, inevitable stream discharge of effluents requires the highest practicable treatment technology to be applied.

At present, the industrialized hog production in Poland is limited to a little over five percent, and the country is still in the process of testing the various production technologies and wastewater/manure/disposal systems.

The present project will be confined to large piggeries as they create a much larger environmental impact than the cattle farms due to more offensive

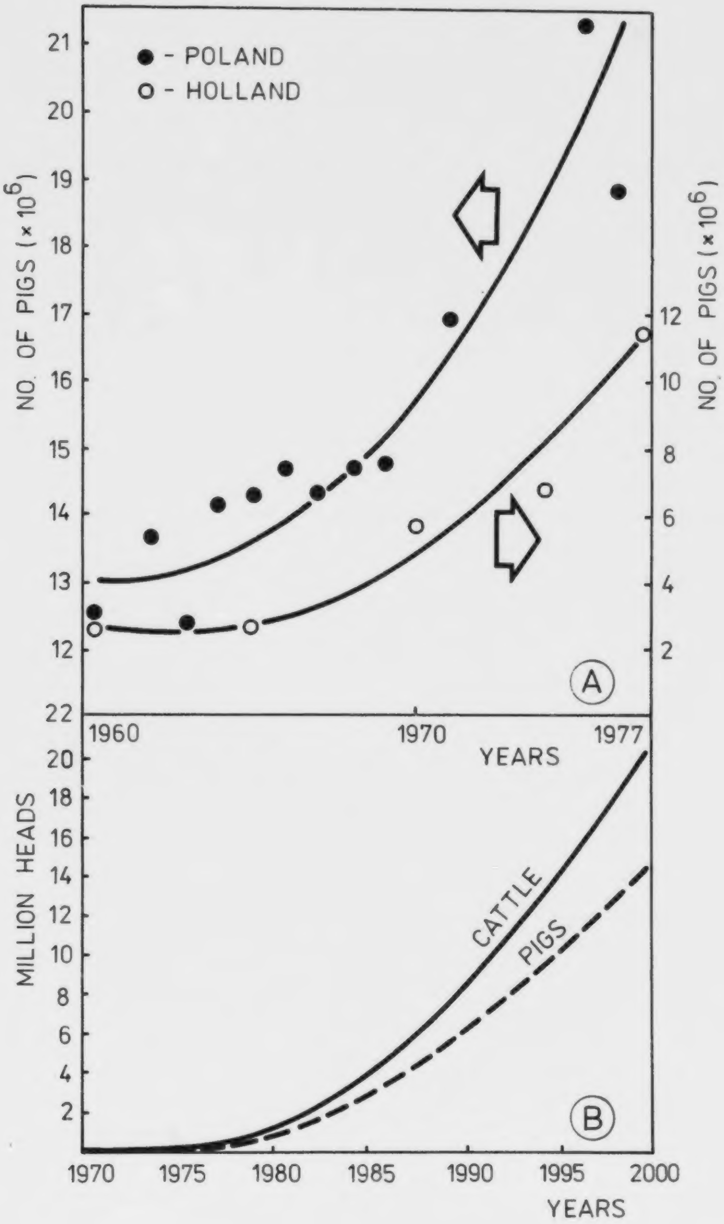

Figure 1. (A) Overall hog production in two countries; (B) Planned production increase of the industrial farms in Poland.

odors, larger waste volumes and difficulties encountered during conventional treatment and pretreatment before land disposal. The large piggeries were purchased by Poland for trial purposes as the whole package with adjoining waste treatment equipment. The practice has disproved many of the systems, however, no formal assessment of the treatability of effluents from large piggeries has been made. The project should answer the demand for: adequate characterization of the raw effluents, knowledge of treatment efficiencies attained by various unit processes and operations, alternative more economical and more efficient treatment and pretreatment systems.

The overview of foreign practice in piggery wastewater treatment obtained during visits to plants, in USA, Italy, Holland and Scotland as well as the thorough literature perusal have documented the lack of data on treatment of dilute wastewaters. The trends in these countries, although a rapid increase in the overall pork production and the average farm size is evident, is to keep the farms small and manure as concentrated as possible through recycle and decreased water consumption. Thus, available information concerns concentrated effluents for which the process economics are different. The present project will describe and charaterize the full scale practice of treating the dilute pig wastes and evaluate the technological, economical and environmental applicability of the novel alternative wastewater treatment processes featuring biogas production and single cell protein recovery.

PROJECT SCORE

Based on mail surveys, literature data, field trips and on-site long-term round-the-clock surveys, a summary of the present hog production and wastewater treatment trends will be presented. Treatment effects will be given and economic efficiency of various practiced unit processes will be critically evaluated. Both practiced and promising future polishing treatment process will be discussed. In-depth feasibility studies will be presented, leading to the optimization of the operation of presently used systems treating effluents for stream disposal and the novel systems proposed for the future use. Finally, a set of proposals will be given, as to the required treatment for stream disposal and for agricultural utilization or combined treatment with other effluents. The proposals will be based on comparison of costs, treatment effects and non-economic factors which are beginning to play an important role in the agricultural industry, e.g. the shortage of qualified manpower, sight and odor nuisance, lack of adequate land for agricultural disposal and other. The desirable development trends will conclude the report.

SECTION 4

PRESENT PIGGERY WASTE TREATMENT PRACTICE

HOG PRODUCTION AND EFFLUENT TREATMENT TRENDS

There are close to twenty industrial hog production technologies used. The most popular include: the Agrokomplex which is Hungarian, Emona which is Yugoslavian, Gi-Gi which is Italian, Bisprol which is Polish, Achmidt-Ankum which is West German, and Poznan which is Polish. The basics of production are similar; the major differences are confined to: the methods of insemination, size and number of reproducing sows, the cycle of young pigs and fattened hogs production, the age of wheaning, final product weight, degree of mechanization and various technologies of wastes removal from the buildings.

The typical Agrokomplex technology consists of the following animals (5): sows in various physiological stage - 870; young pigs up to 28 days old - 1,450; young pigs 28 to 65 days old - 1,900; breeding sows - 147; breeding boars - 29; fattening pigs - 6,200; which totals 10,596 animals. Since the usual loss during the first 65 days is ten percent and only four percent during fattening, animal production of the farm is (870 x 9 x 2.3) x (1 - 0.14) = 15,487 pigs/year, at 105 kg/pig, assume 2.3 litters/year/sow and 9 pigs/litter, at 14 percent death rate.

The farm depicted in Figure 2 consists of seven multifunctional buildings for sows with young and fattening pigs with 960 head each without natural lighting, one building with weak lighting for pregnant sows and one well lit building for loose sows, replacement sows and boars. Several other designs are in use, notably radial arrangement of the major feeding buildings or two story buildings fit for battery production, i.e. two- or three- story cages housing young and fattening pigs.

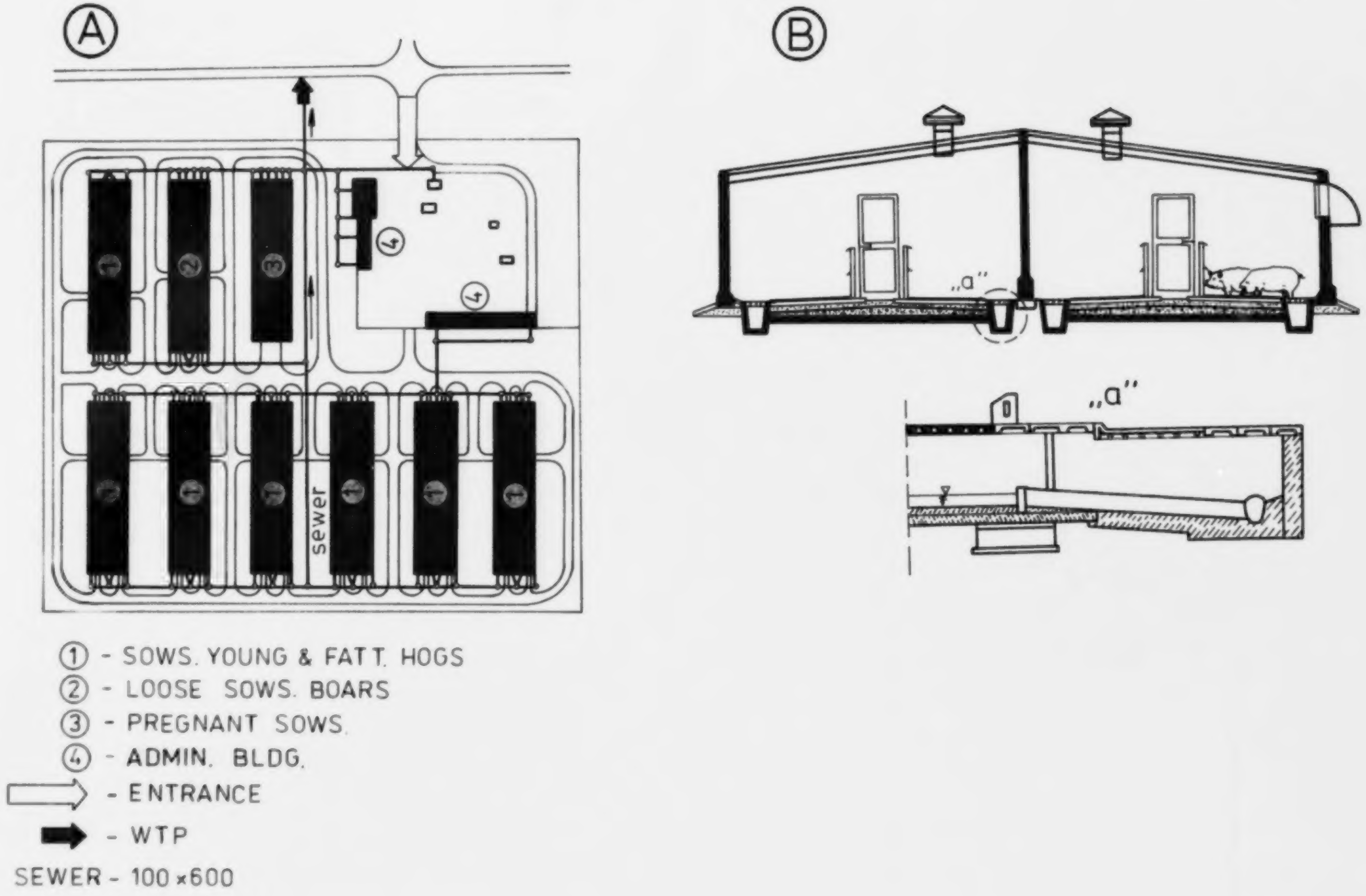
A
B
4
4
1
2
3
sewer
,,a"
,,a"
① - SOWS. YOUNG & FATT. HOGS
② - LOOSE SOWS. BOARS
③ - PREGNANT SOWS.
④ - ADMIN. BLDG.
- ENTRANCE
- WTP
SEWER - 100 × 600

Figure 2. Layout and cross-section of an Agrokomplex Farm A with 10.5 thousand head.

There are two definite wastewater disposal trends which depend on the concentration of effluents. For large farms with dilute effluents, the trend is to treat the wastes for stream disposal as it is frequently impossible to utiliize agriculturally the quantity of produced effluents on year-round basis. For smaller farms various mechanical methods of manure removal are introduced to limit the water content and different methods of odor removal are practiced here are the distance for tank transport and quantity and availability of diluting water that at times has to be applied.

WASTEWATER QUALITY AND QUANTITY

The evaluation of water and wastewater management systems is based on the in-depth survey of three plants (7) and on a mail survey of other treatment plants and regional water authorities.

Wastewater Quantity

Plants A and D have been studied in depth, serving respectively 10.5 and 18 thousand head farms - both are of the Agrokomplex technology. The designed daily water use at these plants is (5): production zone - 145.0 m^3/d, sanitary zone 2.2 m^3/d, administration - 9.1 m^3/d, waste treatment plant - 15.0 m^3/d which totals 171.3 m^3/d for 10.5 thousand head. The quantity of wastewaters expected by designers is (171.3 - 50.5) = 120.8 m^3/d, since close to 50 m^3/d is incorporated in the product (5). The waste treatment facilities are designed based on the overall expected water demand, i.e. on the average 17 $dm^3/hog/day$.

The present day experience with large hog farms indicates that very few wastewater treatment facilities are able to meet desired effluent quality because of the significantly increased water use at the farm and operational problems at the treatment plant. The water use greatly exceeds both the basic hog requirements and the hygienic needs, which are estimated at 9 to 13 $dm^3/d/$ hog over 90 kg liveweight (LW) (10), and amount to 20 to 40 $dm^3/d/hog$. The reason for such an abundant water use lies in the design of the houses, in improper washing practices, and leakage increasing with the size of farm, and also with the design of treatment facilities, e.g. the use of tap water for filter backwash.

Typical animal houses are depicted in Figure 2-B. The collecting channels are flushed by manure impounded with sluice gates, water is fed by nipple feeders and is used for hoseflushing the fattening pens. The amount of water saved when careful management practices are strictly observed is illustrated in Figure 3 which shows the distribution of effluent quantity after the completion of the modification program launched by the authors at Plant A, a modified 10,000 head Agrokomplex farm, with significantly increased breeding department (over 900 sows). The changes included both the farm and treatment plant modifications (9). The installation of pressure tanks and pressure nozzles on hoses for manual cleaning was one major cut in the water used. Other cuts included elimination of sewers infiltration and introduction of additional piping for filter backwashing with clarified effluent. Although water management systems differ among farms, the quantity of inflowing raw wastes has the most profound effect on the efficiency of the whole treatment plant in any hog farm. Inherent hourly, daily and seasonal variability in wastewater flow and concentration, usually assumed as (8): daily variability $N_d = Q_{max,d}/Q_{ave,d} = 1.7$ and hourly variability $N_h = 24\ Q_{max,h}/Q_{max,d} = 1.8$ were found much higher in this study and equalled $N_d - 2$, $N_h = 3$ to 5. When this is superimposed on the excess base water use, it significantly adds to an increase of instability factors in all unit treatment processes and large fluctuations in the resulting final effluent quality.

In actual practice the unit and overall water use is much larger than expected by designers. Plant D has had 29 $dm^3/d/hog$ water use after significant cuts were introduced (11), other farms were found to have even higher unit water requirements, at extremeness, the values of up to 45 to 53 $dm^3/d/hog$ were quoted (10).

Wastewater Quality

Somewhat irregular cleaning and feeding procedures result in daily, weekly and even in seasonal variations in wastewater quality and quantity. Figure 3 illustrates the BOD_5 and COD monthly variability in raw wastewaters in the half-year of studies at plant A. Daily and hourly variability is illustrated elsewhere (12).

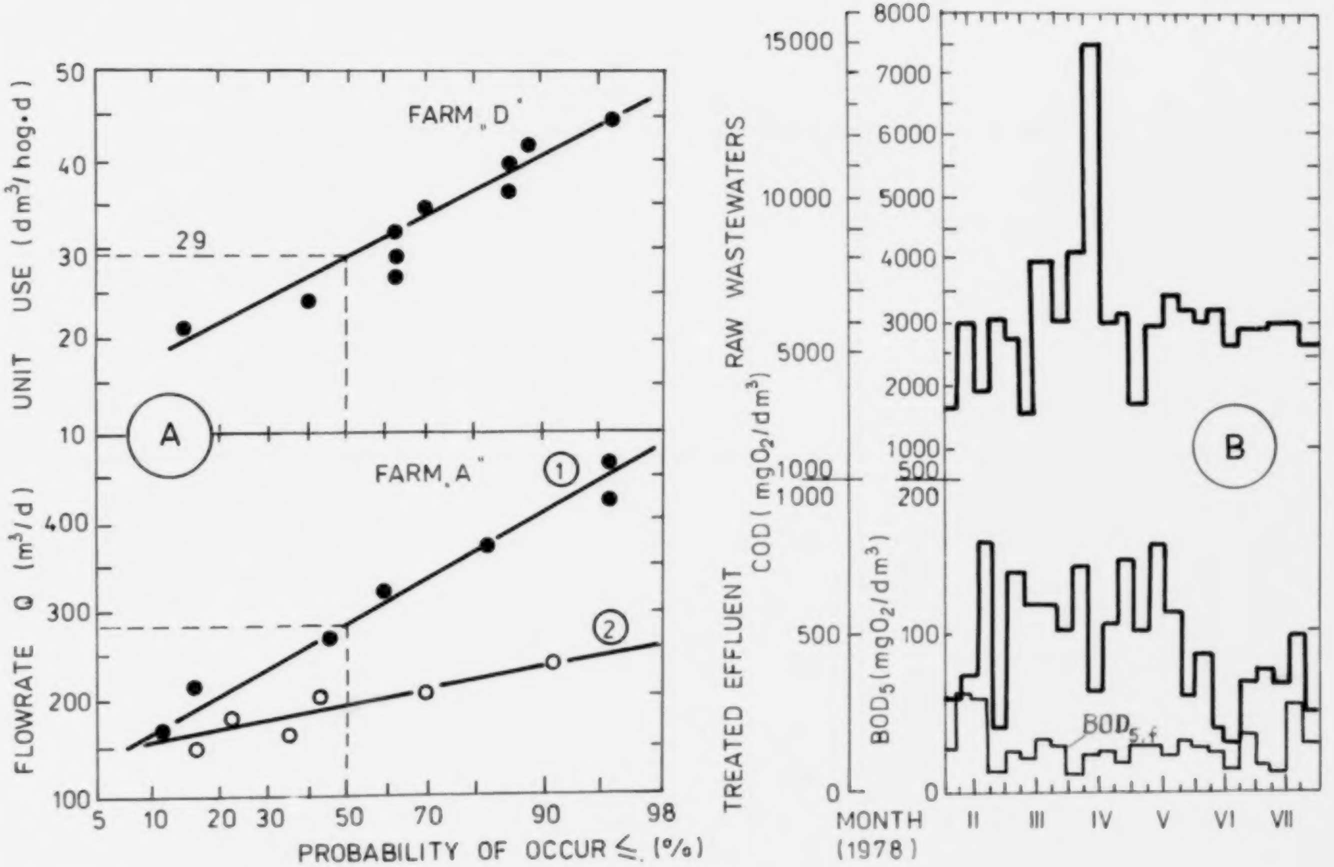

Figure 3. (A) Water use at Farm D and Farm A before modification in 1979-curve 1, and after modification - curve 2; (B) Variability of wastewater concentration at Farm D.

Averaging the data collected by numerous authors and compiled by Loehr (13): 0.12 kg BOD_5/d/hog; 0.35 kg COD/d/hog; 0.121 kg SS/d/hog; 0.287 kg TS/d and 0.254 kg VTS/d; and compiling results of Dragun's work (4) and authors' own research, one obtains the basic unit raw waste load (RWL) from one hog assumed to have a lw of 50 kg. Dividing these values by average (50 percent) wastewater volume output, which for plant D is 28 l/hog/d, one obtains the concentrations that compare fairly well with the data actually measured (Table 1).

TABLE 1. THEORETICAL ESTIMATION OF POLLUTANT CONCENTRATIONS IN EFFLUENTS FROM LARGE PIGGERIES AND COMPARISON WITH ACTUAL AVERAGES FOR PLANT D

Pollutant	RWL g/d/hog			Concentration mg/dm^3			
	Loehr	Dragun	Authors	Loehr	Dragun	Authors	Actual
BOD_5	124	121	136	4,430	4,320	4,860	5,000
COD	352	363	400	12,570	12,960	14,300	15,000
Total Solids	287	-	-	10,250	-	-	12,300
Volatile Solids	254	-	-	9,070	-	-	-
Total SS	121	-	-	4,320	-	-	7,700

Note: Concentration based on q(50 percent) = 28 dm^3/d/hog.

In order to give the designer a set of numbers for making preliminary design estimates fourteen large farms were surveyed. The analysis was performed by fitting the normal probability curve as in Figure 4-A and finding the average (50 percent), the standard deviation and the risk design value of 95 percent as the maximum. The characteristic values are given in Table 2.

Attempts were made to differentiate between the water management practices of the three sizes of plants that made up the 14 plants studied, i.e.: 10, 18, and 24 thousand head. It was confirmed that there are no statistically meaningful differences between the various sizes.

The raw wastewater quality results were analyzed as shown in Figure 4-B. Such correlations allow for establishing a set of design equations which are valid in a very wide range of concentrations. This mechanism of verification of animal wastes concentrations data was found of utmost importance due to analytical difficulties experienced by various reporting sources.

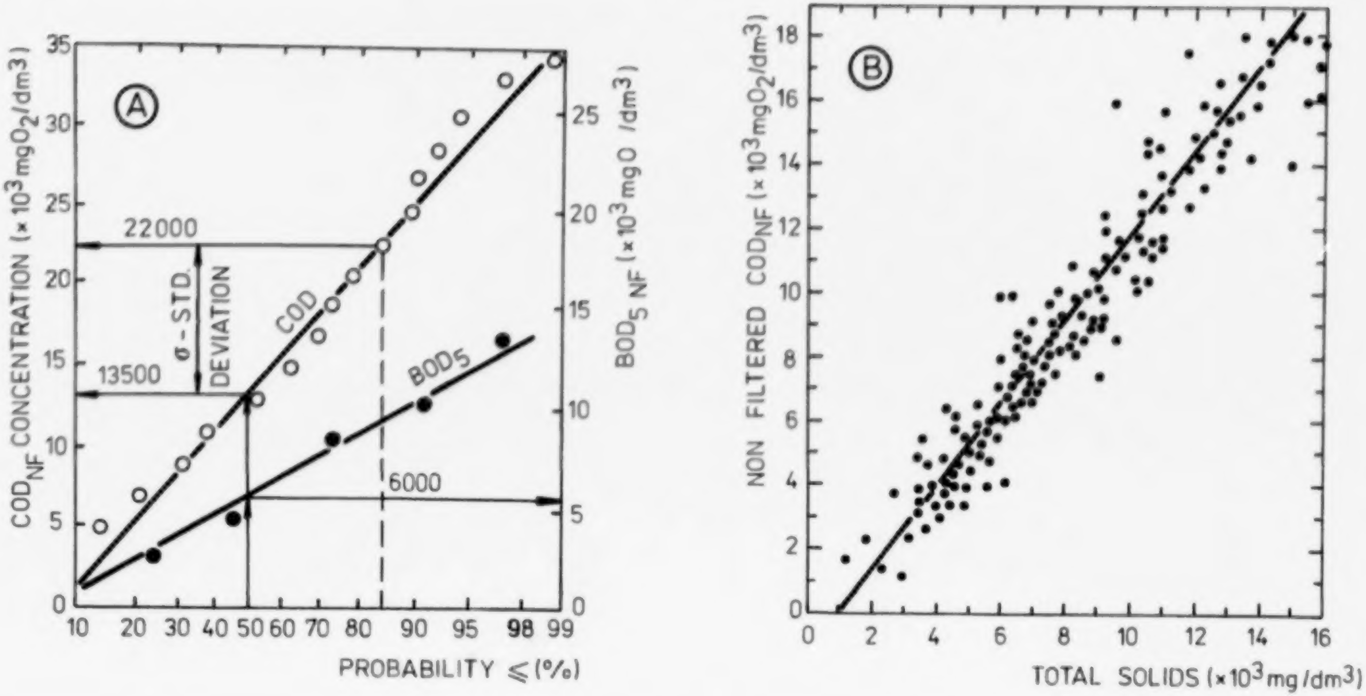

Figure 4. Raw wastes characteristics: (A) Concentration probability based on pooled data from 14 farms; (B) Reggression of COD_{nf} on total solids.

TABLE 2. AVERAGE CONCENTRATIONS OF POLLUTANTS IN WASTEWATERS FROM 14 LARGE FARMS (MG/DM^3)

Pollutant	Mean (50%)	Max (95%)	Std. Deviation
BOD_5 - non-filtered	6,000	11,800	3,000
COD - (nf)	13,500	28,300	8,500
Permanganate value (nf)	3,100	-	-
$N-NH_3$	600	1,700	550
Phosphorus - P_2O_5	750	1,700	600
Potassium - K_2O	550	920	240
Total suspended solids	6,400	-	-
Aluminum Al^{+3}	8.0	30.0	12.0
Zinc Zn^{+2}	4.0	9.0	3.2
Manganese Mn^{+2}	0.9	3.0	1.3
Copper Cu^{+2}	0.15	2.2	1.20
Iron Fe^{++}	1.0	-	-
Chromium Cr (total)	0.05	-	-
Lead Pb^{+2}	0.5	-	-

The need for adequate screening of literature data has also been emphasized by other writers (14). The relationships for raw pig wastes attained here are:

$$COD_{nf} = 2.4\ (BOD_{5,nf}) + 2000 \qquad \text{(Farm A)}$$

valid for $BOD_{5,nf} \geq 1000$ mg O_2/dm^3, and

$$COD_{nf} = 3.09\ TOC + 100 \qquad \text{(Farm A)}$$

$$COD_{nf} = 1.33\ TS - 1200 \qquad \text{(Farm A)}$$

$$TS = 1.38\ VS + 500 \qquad \text{(Farm A)}$$

$$BOD_{5,nf} = 1.66\ BOD_{5,f} \qquad \text{(Farm A)}$$

Data for various farms yielded:

$$COD_{nf} = 2.4\ BOD_{5,nf} + 1400$$

TREATMENT SYSTEMS USED; PROBLEMS ENCOUNTERED

There are several unit processes and waste treatment systems used before stream disposal; while the technology of treatment prior to land disposal is confined to lagooning with/or without aeration. The treatment systems depicted in Figures 5 and 6 are the most common used.

The first system (Figure 5), Vidus (imported from Hungary), the most common in this country, consists of fine dynamic screening (1 mm mesh), followed by 24 hr primary aeration and chemical coagulation and activated sludge (12 + 14 hr) aerated with surface aerators. This is followed by a submerged filtration and chlorination. The excess sludge is fed into primary aeration tanks and evacuated after alum coagulation with primary sludge to a separate gravity thickener. Due to a large $AL_2\ (SO_4)_3$ coagulant dose (1000 mg/dm^3), poorly dewatering sludge is produced, the disposal still remains the major problem although positive results are obtained with land disposal. The cost of the treatment plant is high and amounts to 10 to 20 percent of the capital costs of the farm, depending on size (15). The annual running costs amount are high and run around 10 percent of the capital costs; however, the plants still seldom achieve the expected effluent quality ($BOD_{5,nf} = 50$ mg O_2/dm^3, $COD_{nf} =$ 500 mg O_2/dm^3) due to operational difficulties encountered with this sophisticated multistage treatment process.

The Vidus type plant has been modified within the realm of the project in Farm A (9): the coagulant dose was optimized down to below 600 mg/dm^3; activated sludge content was increased to 5000 mg $MLVSS/dm^3$; the anaerobic sludge content was increased to 5000 mg $MLVSS/dm^3$; the anaerobic denitrifying biofilter was rebuilt and the sponge media was replaced with coke; and sludge disposal problems were solved. The major disadvantage of the system is its vulnerability to irregularities of flow and large quantities of chemical sludge produced.

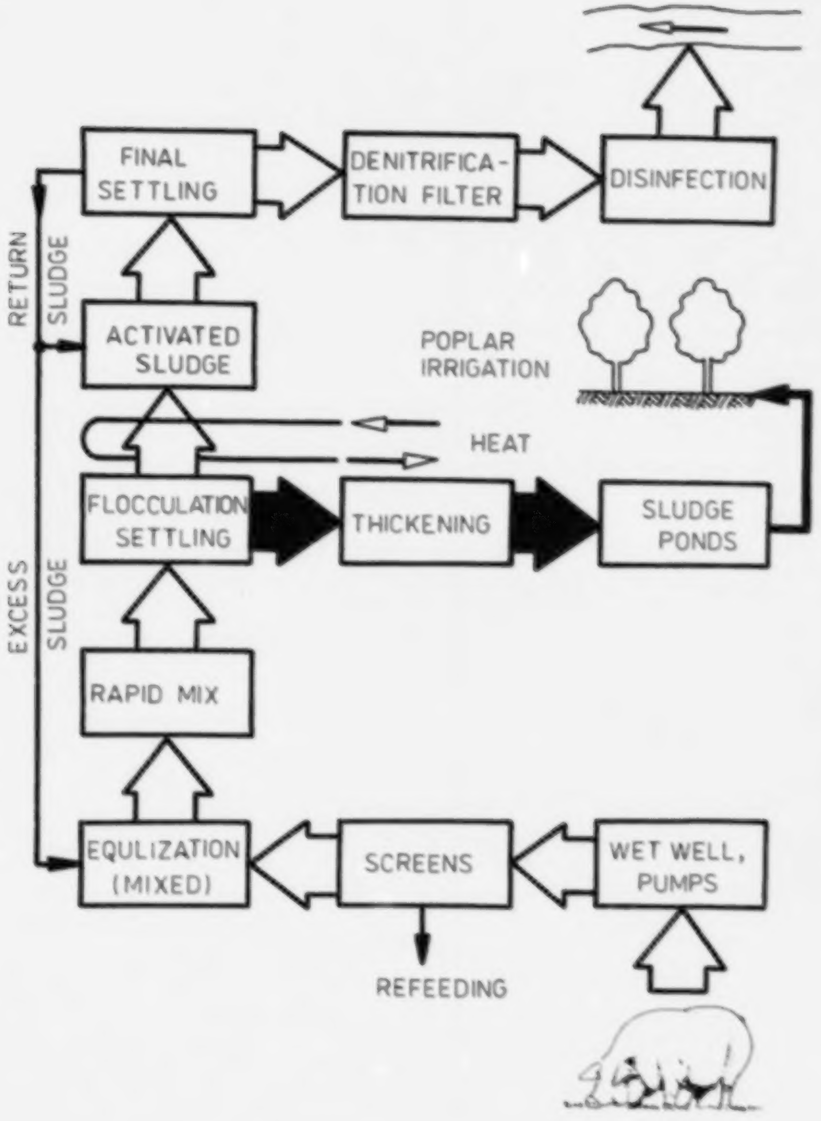
FINAL SETTLING
DENITRIFICATION FILTER
DISINFECTION
RETURN SLUDGE
ACTIVATED SLUDGE
POPLAR IRRIGATION
HEAT
FLOCCULATION SETTLING
THICKENING
SLUDGE PONDS
EXCESS SLUDGE
RAPID MIX
EQULIZATION (MIXED)
SCREENS
WET WELL, PUMPS
REFEEDING

Figure 5. Layout of Vidus type Plant A modified by authors.

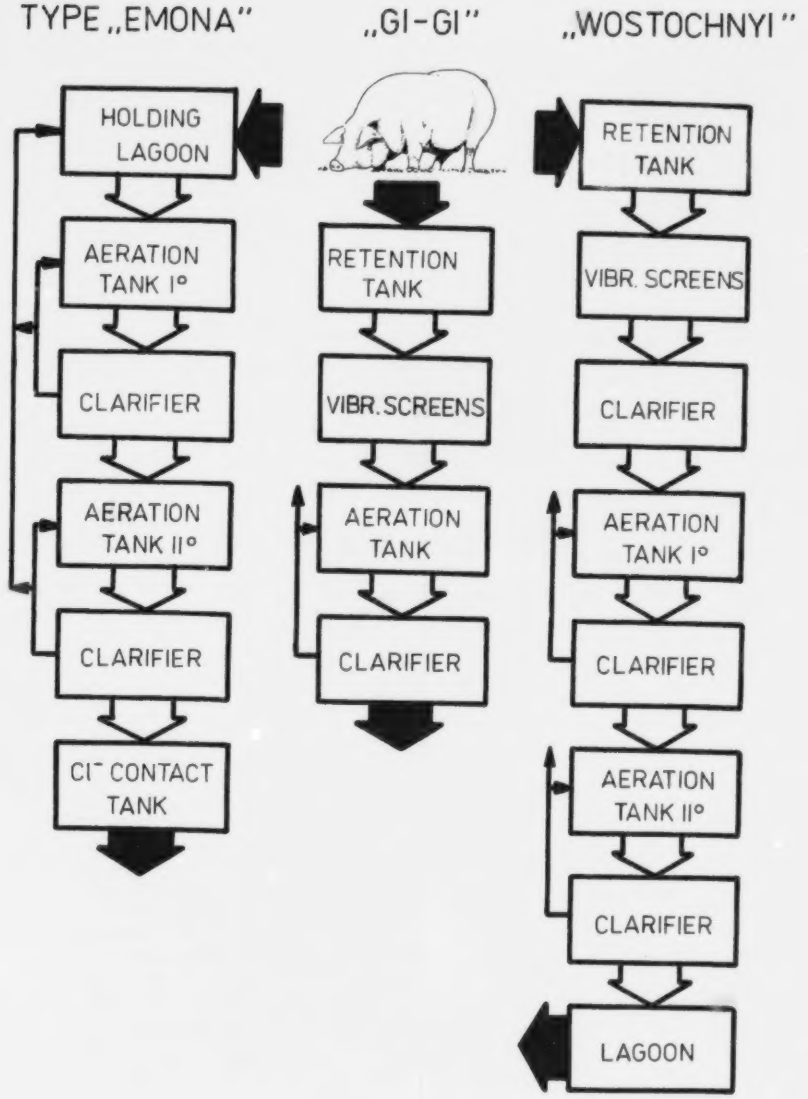
TYPE „EMONA"
„GI-GI"
„WOSTOCHNYI"
HOLDING LAGOON
AERATION TANK I°
CLARIFIER
AERATION TANK II°
CLARIFIER
Cl⁻ CONTACT TANK
RETENTION TANK
VIBR. SCREENS
AERATION TANK
CLARIFIER
RETENTION TANK
VIBR. SCREENS
CLARIFIER
AERATION TANK I°
CLARIFIER
AERATION TANK II°
CLARIFIER
LAGOON

Figure 6. Presently used treatment systems for dilute piggery wastes.

The overall sludge volume may amount up to 50 percent of wastewater volume in heavily overloaded plants. The sludge is difficult to dewater; the initial work on agricultural applicability has proved promising.

The Emona system, imported from Yugoslavia (Figure 6), features 5 months lagooning followed by 18 hrs activated sludge treatment as first stage and 8 hrs aeration as second stage. The initial costs are low, approximately 3 percent of the farm cost, however, the system exhibits problems due to high influent organics concentration after primary treatment due to sludge anaerobic release and low temperatures in the activated sludge following the lagoon.

The Gi-Gi system (Figure 6), licensed from Italy, features primary dynamic screening followed by aeration for 48 hours, at approximately 0.5 kg BOD_5/kg MLSS,.d and final clarification. The system's capital costs are some 8.5 percent of the farms cost, and the operation costs are 13 percent of the plants capital costs (15). The major problems are hydraulic overloading and the nature of excess sludge which results in very rapid clogging of drying beds. The system has proved to yield inadequate effluent quality.

This brief comparison of technologies and costs (based on 35 thousand annual pig production and the overall costs of the farm equal to 250 million zloties, where 1 U.S. dollar = 20 zloties, zl) proves that designers have made several errors, such as: placing the low rate processes before high rate processes; or the general selection of wastewater treatment processes without taking into account the resulting sludge problems. The performance failures of several systems are related to the problems most common in this field, as also noted recently by Evans (16), i.e. unsatisfactory operation and maintenance and the type of design requires highly skilled personnel seldom available for small flow-rate plants, in rural areas.

These rather complicated aerobic technologies are used in other countries as well, often with acceptable results, however, at high operational costs.

The Wostochnyi plant (Figure 6) used in USSR, (18) features two-stage activated sludge followed by lagooning (facultative) and reportedly yields good removals in spite of heavy load of disinfecting and bactericidal agents.

Activated sludge is also used in East Germany, as in the 12 thousand head farm in Halle-Nord where 8 + 10 d aeration followed by 8 d lagooning yields influent/effluent concentrations ratio of BOD_5 - 13,800/180 and COD - 33,000/1500 at a cost of 0.9 mln DM and O-M costs of 15.51 DM/ton LWK, where energy use makes 48 percent of the running costs (17). One DM = 0.45 U.S. dollars.

In the subsequent chapters the discussion will be confined to the results of unit operations on wastes from Agrokomplex farms and the Vidus systems since they have been used most often in this country.

EFFICIENCY OF TREATMENT PLANTS PRESENTLY IN USE

The efficiency of the various treatment system steps, at the plants studied, varied depending on the irregularities of flow-rate biological process loading and sludge content, coagulant dose, temperature, and to the major extent on the level of skilled operation.

The efficiency of mechanical screening at Plants A and C is presented in Figure 7. It follows from this plot that average COD removal is only 10 to 18 percent, while suspended solids (SS) removal amount to 22 percent. Comparing these results with data for other plants, it follows that COD_{nf} removals vary from 10 to 15 percent.

Full scale coagulation performed routinely in all plants of this type yields removals of total COD ranging from 40 to 85 percent, with bulk of data around 65 percent. Plant A data analysis revealed no correlation between the dose and effect, due perhaps to the changing pattern of solids discharge from the farm.

Biological Treatment

At Plant A two completely mixed (surface) aeration tanks are employed treating primary effluent of average incoming BOD_5 strength of 580 mg O_2/dm^3. At present the concentrations have increased several times, however, the

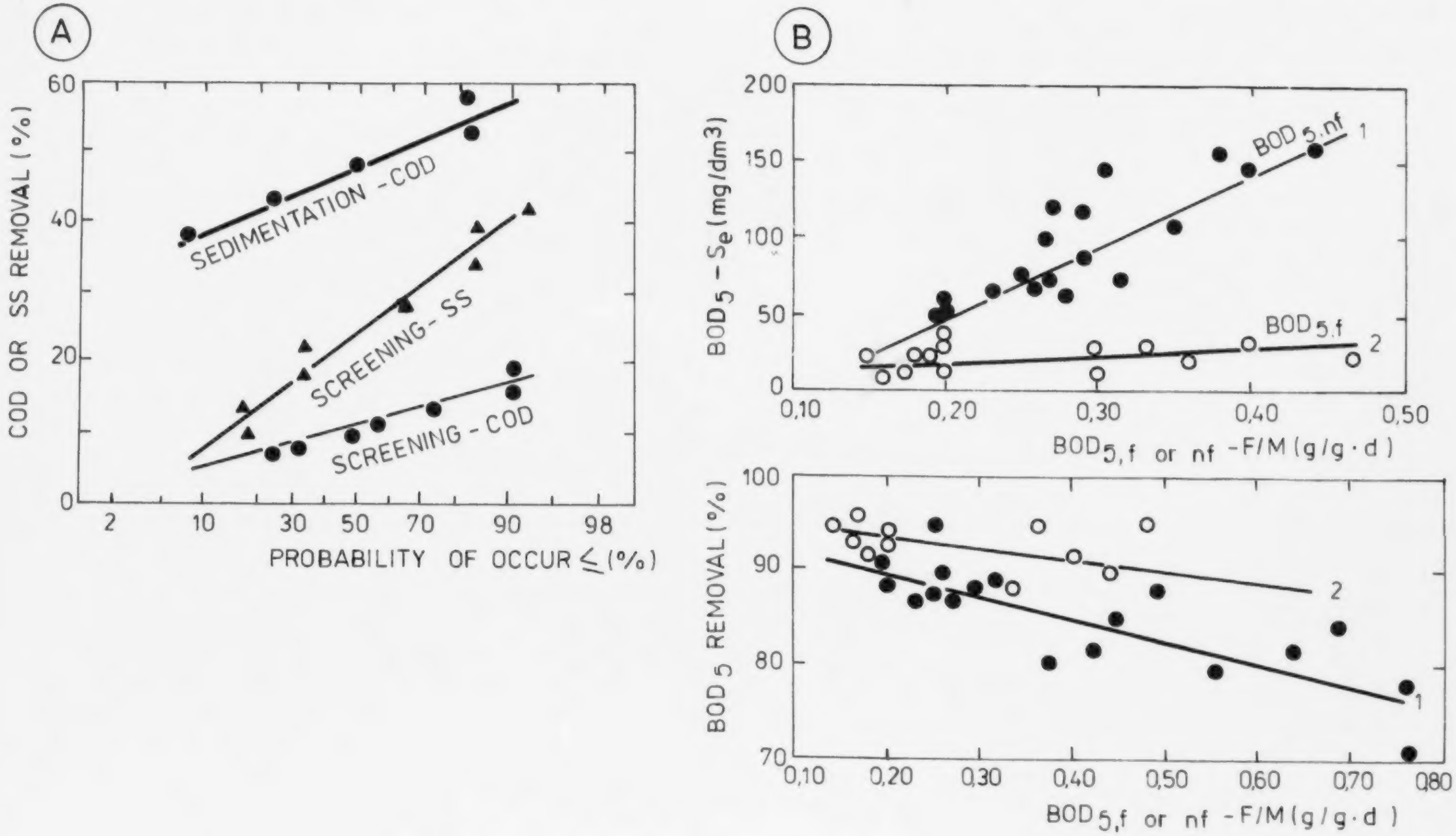

Figure 7. (A) Efficiency of screening at Plant A and sedimentation at Plant C; (B) BOD_5 removal efficiency at Plant A as affected by sludge loading - F/M.

retention time increased correspondingly and the mixed liquor suspended solids (MLSS) were also increased. The design activated sludge parameters versus the actual working regime during the time of this study (1978) were presented in reference (11) - data before modification. The present parameters are X = 5000 mg/dm^3 (values up to 7000 mg/dm^3 MLSS were applied successfully), t = 24 hrs, effluent from chemical clarifier $S_o = 2 + 4$ g O_2/dm^3 - COD, food to mircroorganisms ratio F/M = 0.5 to 0.7 kg O_3/kg/d.

The removal efficiency in the activated sludge system depends on many factors, the most important being F/M or sludge loading, temperature and sludge age, i.e. the sludge recycle practices. There are also indirect factors that influence the biological system performance, such as total dissolved solids (TSS), sludge volume index (SVI), zone settling velocity, etc.

A rather well defined relationship between the sludge loading and BOD_5 removal ratio is presented in Figure 7-B. The F/M ratio had a pronounced effect on the effluent suspended solids carryover from the settling tank overflow, before modification. The correlation of the effluent BOD_5 versus BOD-F/M for both soluble and the total values illustrates this best. The significance of adequate final clarification is evident from this graph. Soluble effluent BOD_5 stays relatively unchanged over a large range of F/M variations, while total BOD_5 values increase rapidly with the increasing loading. This should be well substantiated by sludge volume index changes. The correlations of SVI versus F/M for both BOD_5 and COD, were, however, very weak, as described elsewhere (11). Since most regulations on effluent concentrations are based on the total BOD_5, maintaining the appropriate SVI is of paramount importance, thus the need for polishing treatment.

It should be noted that data interpreted here comes from plants in normal operating regime, although the authors have prepared instruction manuals for the maintenance crew at Plant A. Thus, the operating parameters varied. This is fully described by authors in other papers (11).

The equation used for calculation of the kinetic K constant is the substrate kinetic model of Grau and Eckenfelder:

$$\frac{S_o - S_e}{X_a \cdot t} = K \frac{S_e}{S_o} \tag{1}$$

The kinetic rate constants for Plant A and other plants expressed in COD units are presented in Figure 8, where curve 1 is for soluble COD_f data.

The operation of the process at varying temperatures allows for estimation of the temperature correction factor for the rate constant, according to the Arrhenius equation:

$$K_T = K_{20} \cdot \Theta^{T - 20} \tag{2}$$

The plot of log K_T vs Δ T for BOD_5 data from Plant A prior to changes yields the value of $\Theta = 1.053$ and the average $K_{20} = 6.6\ d^{-1}$ (see Figure 8). Judging by the spread of data, the value of Θ needs further verification, it is, however, valid for estimation of dilute wastewaters from Plant A.

The performance of activated sludge after modification is presented in Figure 9. Individual unit process efficiencies are presented in Figure 10.

Polishing Treatment

The unstable at times, operating conditions result in significant deterioration of biological effluent quality due to solids carryover which may be correlated as $BOD_{5,nf}$ versus SS:

$$BOD_{5,nf} = BOD_{5,f} + a \cdot SS \tag{3}$$

where "nf" and "f" represent non-filtered and soluble values of BOD_5, "a" is the slope of the curve, and SS the total suspended solids. In the case of Plant A:

$$BOD_{5,nf} = 30 + 0.20\ TSS \tag{4}$$

In order to alleviate this problem in Plant A an existing anaerobic flooded biofilter has been adopted as a filtration and denitrification filter. The filter, filled with coke and an underlayer of gravel, yields good removals

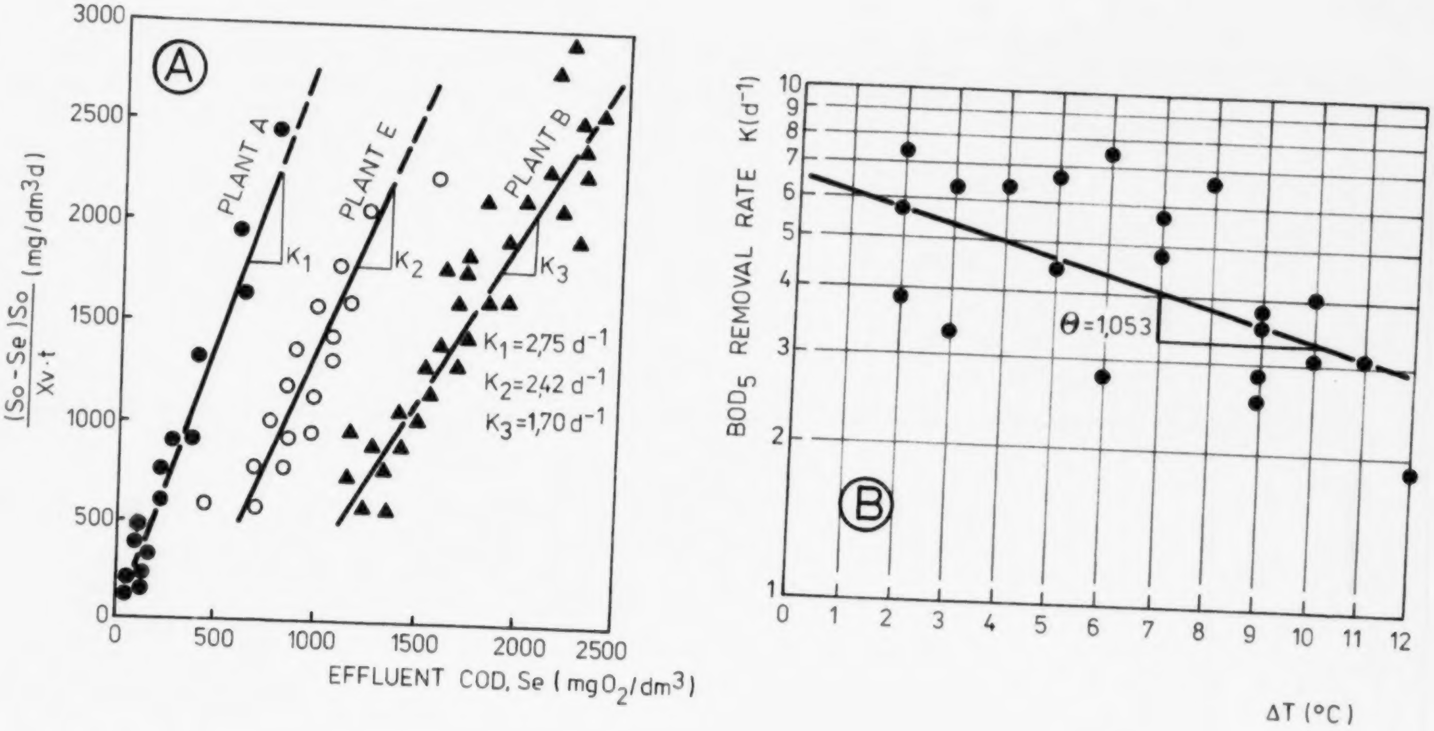

Figure 8. (A) Activated sludge performance at three Vidus plants; (B) Temperature correction calculation for Plant A data.

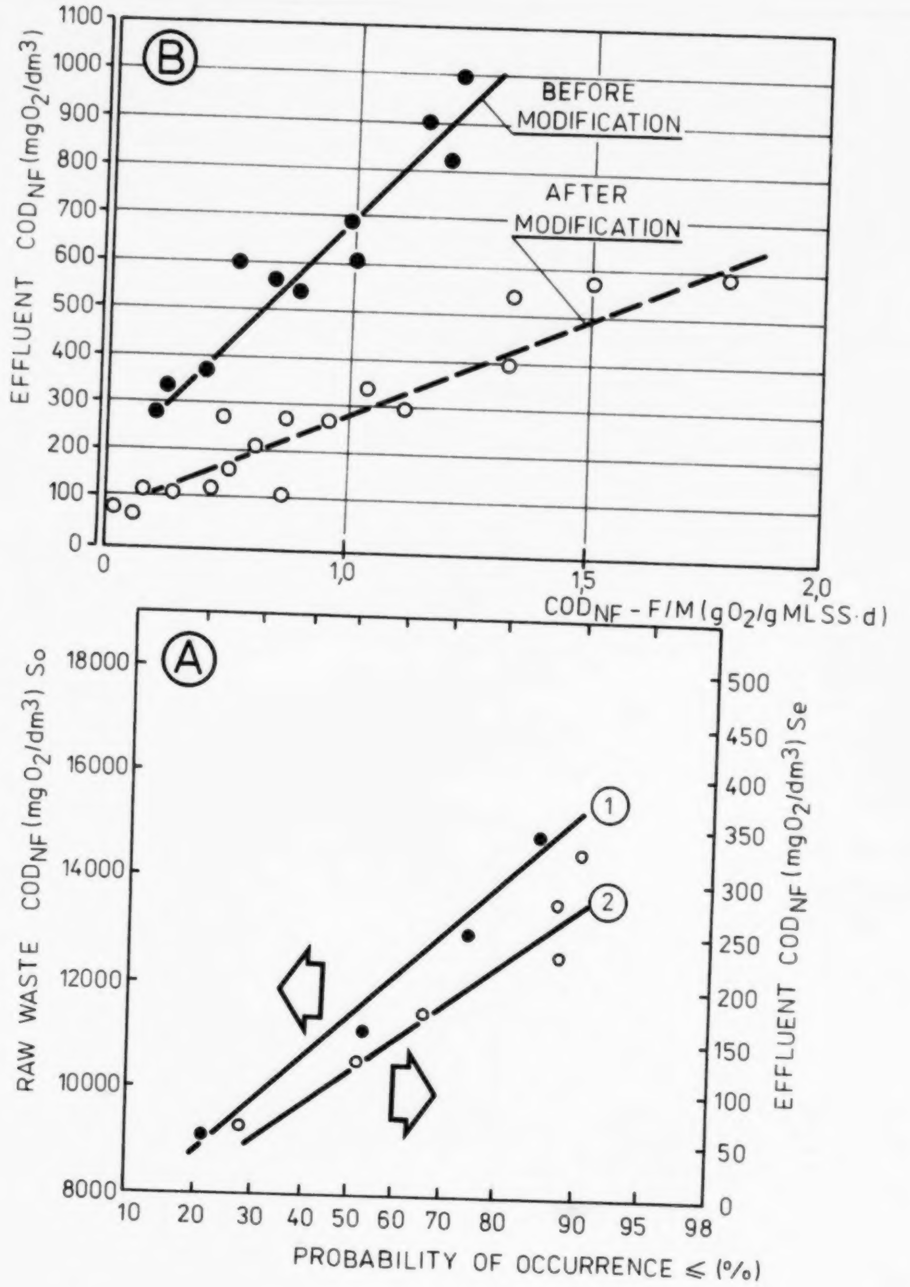

Figure 9. (A) Distribution of raw and effluent wastes COD after modification; (B) Influence of COD_{nf} sludge load on effluent quality; - Plant A data.

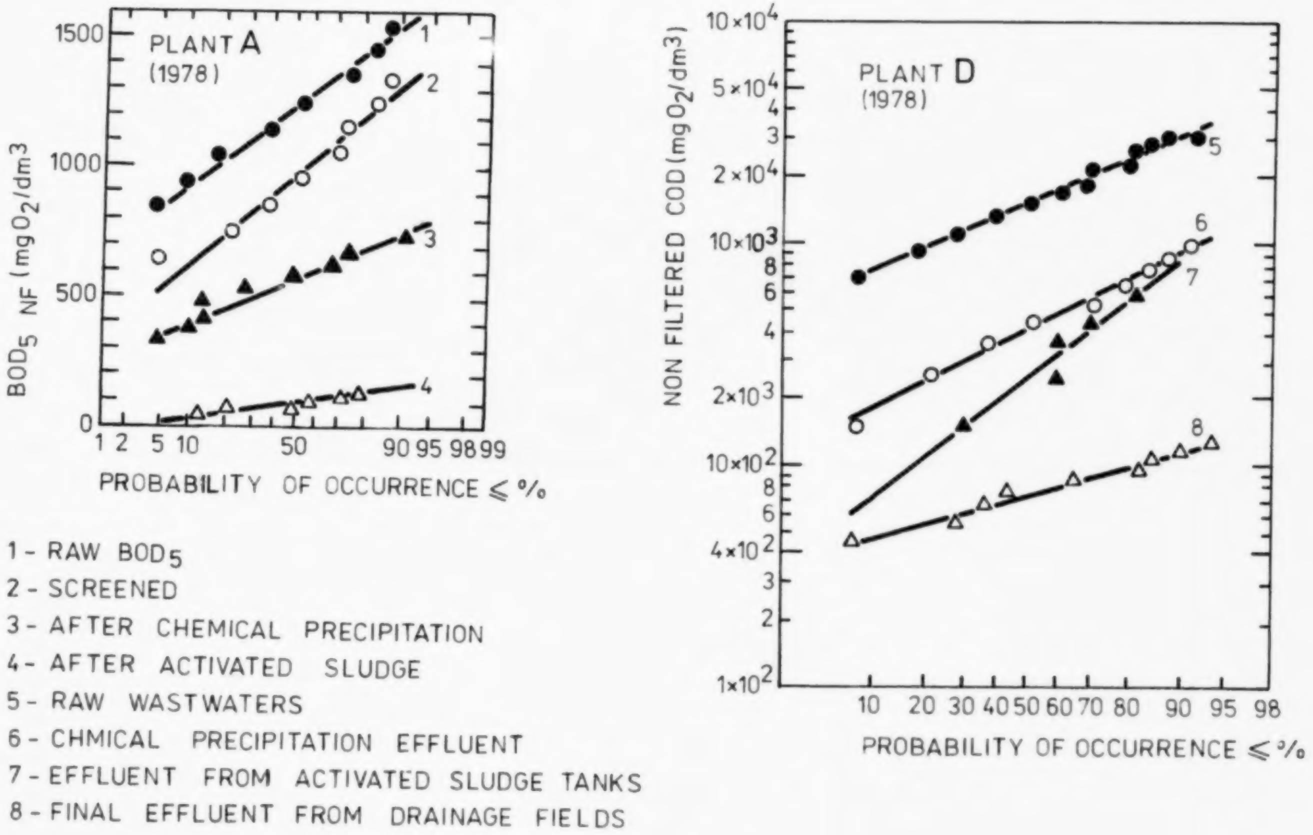

Figure 10. Efficiency of unit treatment processes at two full scale plants.

at varying influent loads and concentrations. The kinetic interpretation of filter removal data according to the authors' model (20):

$$S_e/S_o = \exp(-K/L) \qquad (5)$$

where K (kg/m^3/d) is the gross removal rate coefficient, L (kg/m^3/d) is the volumetric organic loading, yielded $K_I = 2.9$ and $K_{II} = 1.1$ kg/m^3/d.

The anaerobic biofilter at Plant A was responsive to influent substrate concentration and load variations. Thus, maintaining good equalization is of paramount importance at the influent to the biological part of the treatment train. More detailed analysis of the anaerobic biofiltration polishing is presented in Section 7.

ECONOMIC EFFICIENCY OF TREATMENT

The research on five of the large imported wastewater treatment plants has shown high O&M costs which are due to large chemical use and use of oil for heating wastewaters and high power consumption for pumping to subsequent stages, as well as for aeration. The capital costs of the imported treatment plants are also high and may run up to 20 percent of the overall farm costs, as shown in Figure 11 (22, 23).

The analysis of efficiency of the existing treatment plants was performed according to procedures binding designers of the so-called non-productive structures in Poland (24). The basic formula for the economic efficiency index E:

$$E = \frac{J\,(r + s) + K}{W} \qquad (6)$$

where W - magnitude of the utility effect;

J - capital investment (zloties); equal to $J = I(1 + 0.5\, b.r)$ for $b > 1$ year, the value of $b = 2$ was used;

b - time needed for construction (years);

s - average amortization rate;

r - discount rate; $r = 0.08$ was used;

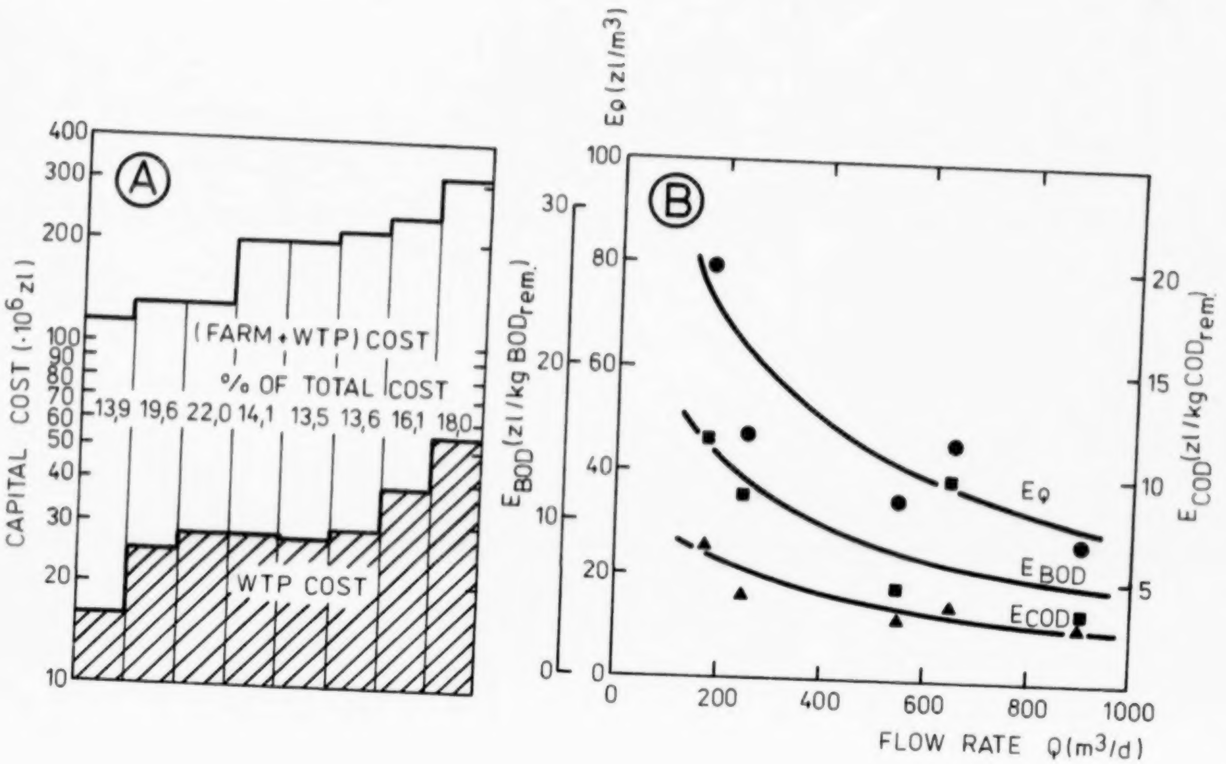

Figure 11. (A) Capital costs of piggery farms and waste treatment plants - WTP; (B) Economic efficiency of treatment as affected by WTP size.

K - annual running (O&M) costs decreased by amortization
I - raw investment costs (zloties).

The economic efficiency index is expressed against either volume of wastewater treated in a year (E_Q-zl/m^3) or in terms of weight of pollutant removed in a year (E_{BOD}-zl/kg BOD_5 removed), by dividing the cost by respective utility effect, i.e. m^3/year of kg BOD_5 removed/year. The evaluation of data collected at five farms is presented in Table 3. Other data, reported by Heidrich et al. (22) revealed the values of E_Q varying from 13.7 to 67.5 zl/m^3 and E_{BOD} = 2.6 to 10.6 zl/kg BOD for the Vidus plants while the values for the "Gdansk" treatment system were E_Q = 56 zl/m^3 and E_{BOD} = 9.4 zl/kg BOD_5 - removed.

Graphical analysis of the economic efficiency data in Figures 11 and 12 shows that there is a definite decrease of the economic efficiency indices with increasing throughput and increasing load removed. Data is significantly scattered because of price changes and various periods in which plants were erected. The indices are much higher, particularly E_Q, than the ones for municipal sewage due to higher concentrations of organics, but also due to overdesign of the equipment.

Taking into account the high costs of construction and O&M as well as non-economical factors such as the difficulty in operation due to employment of highly sophisticated technology and the fact that significant quantity of nutrients are wasted, these waste treatment plants are considered to be a temporary solution for the industry. The present trend is to find alternative cost-effective and energy-wise solutions if the wastewaters are to be disposed to stream. In all other cases smaller farms are to be built and sited so as to enable agricultural utilization of wastewaters.

DISCUSSION AND CONCLUSIONS

Most of the farms seem to have expected smaller water usage, and thus, the wastewater treatment plants are usually hydraulically overloaded. Standards binding design engineers give the water use figures of 15 to 25 dm^3/hog/d

TABLE 3. ECONOMIC EFFICIENCY OF FIVE STUDIED VIDUS-TYPE TREATMENT PLANTS

	Unit	Farm A	Farm D	Farm F	Farm G	Farm H
No. of head	10^3	10.5	21.0	25.5	28.0	11.3
Flow Rate -Q	m^3/d	250	650	550	900	180
S_o -$BOD_{5,nf}$	$g\ O_2/dm^3$	4.0	3.8	6.0	6.4	5.4
S_e -BOD_5	$g\ O_2/dm^3$	0.08	0.24	0.20	0.26	0.18
S_o -COD_{nf}	$g\ O_2/dm^3$	13.2	12.7	12.6	12.1	12.6
S_e -COD_{nf}	$g\ O_2/dm^3$	1.72	0.77	0.66	1.82	0.42
Removal BOD_5	%	98.0	93.7	96.6	96.0	96.6
Removal COD	%	87.0	94.0	94.7	85.0	96.6
I	10^6 zl	20.23	54.70	46.38	45.82	25.16
K	10^6 zl	2.03	4.96	1.83	3.84	2.45
E_Q	zl/m^3	46.7	46.2	34.5	27.05	79.5
E (BOD-removed)	zl/kg BOD_5	11.9	13.0	5.9	4.4	15.2
E (COD-removed)	zl/kg COD	4.1	3.8	2.9	2.6	6.5

NOTE: 1 U.S. dollar is equivalent to 20 zloties (zl).

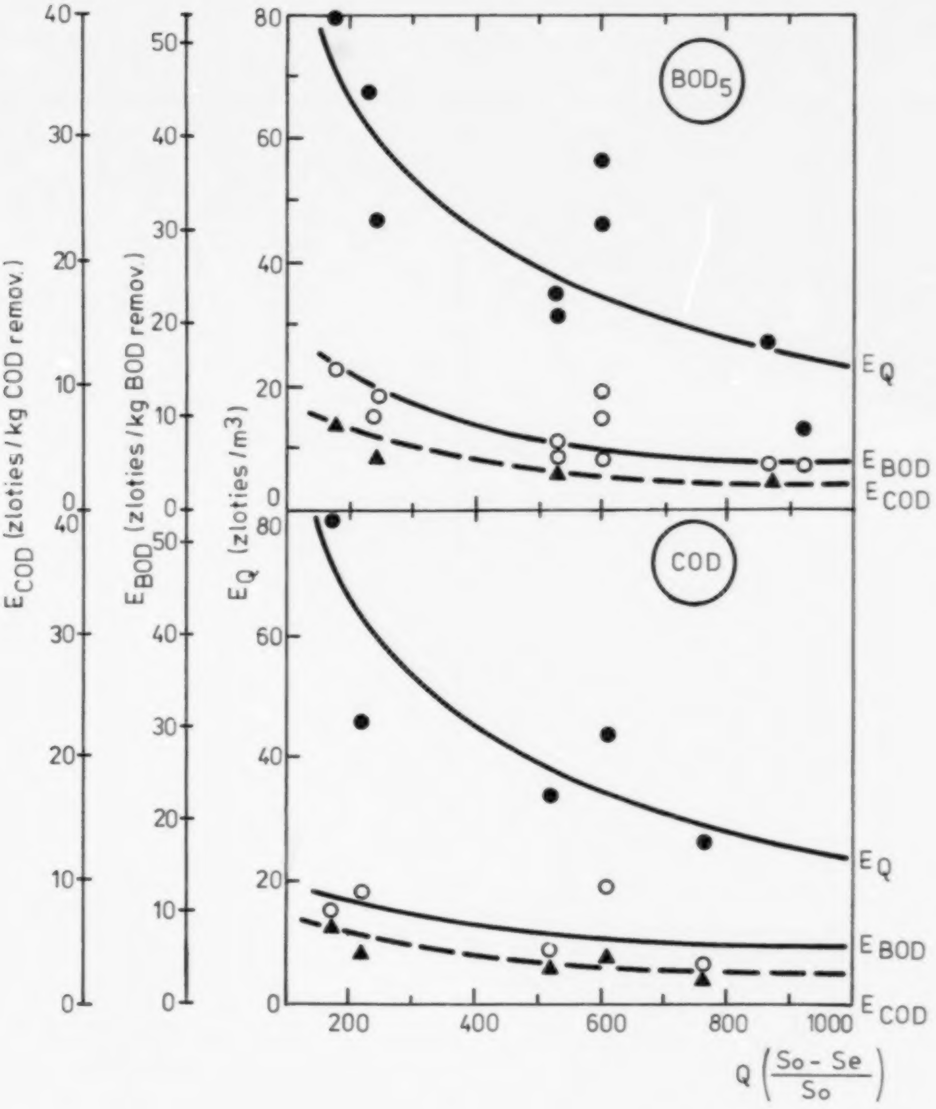

Figure 12. Economic efficiency versus load removed on the basis of $BOD_{5,nf}$ and COD_{nf}.

while real-life practice yields numbers as high as 40 dm^3/hog/d; even higher averages are quoted. Efforts will now have to be made to decrease this water use by modifying the hydraulic transport system towards high pressure cleaning and wastewater recycle for flushing purposes, as demonstrated by authors in this study.

The mechanical (dynamic) screening apparently yielding low solid yields (averaging 11 to 15 percent COD removal and some 20 percent TS) produces sludge of very good dewatering characteristics, and in all cases screens should be included in the wastewater treatment train. This is in accordance with other research findings on solids effects on the treatment efficiency (19).

Coagulation seems to be the subsequent process that could be left in existing plants since it dampens the load variability, however, the dose should be optimized down, as will be demonstrated later.

Activated sludge is a large volume 25 to 48 hr retention process that requires very skillful maintenance due to the nature of the biota (bacterial sludge) with a tendency for bulking, solids carry-over, etc. Our studies have shown that maintaining good settleability of the sludge is crucial to the process overall efficiency. Contrary to other writers (25) who considered it difficult to get down to very low BOD concentrations in the effluent, these studies show good biodegradability of piggery effluents and rather low concentration of refractory organics. The BOD removal rate coefficient at Plant A was found to be approximately equal to 6.6 d^{-1}. The process itself is quite temperature sensitive. The value of temperature factor, equal to 1.053 is higher than that usually assumed for municipal wastes.

The Plant A overall removal efficiency is presented in Figure 9 based on 1980 data. The individual unit process efficiencies (in Figure 10), 1978 data, reveal fairly predictable values, noting that these are averages of the real operating conditions without exclusion of upsets.

It follows that activated sludge is yielding poorer removals in Plant D than in Plant A. Analysis of Plant D biological treatment performance revealed significant upsets of the biota, sludge index values above 600 to 900 (the "normal" value of SVI for pig wastewaters is 150 to 350) and resulting very poor solids separation. Regardless of the reasons for such temporary situations, it is apparent that in such cases the presence of chemical precipitation, although costly, and additional polishing treatment steps buffer the upset of one unit process in the whole treatment train. The soluble BOD_5 values at Plant D have varied from 60 to 100 mg/dm^3 ($BOD_{5,nf}$ = 75 to 300 mg/dm^3) in activated sludge effluent and 25 to 40 mg/dm^3 in the irrigation field effluent (the final treatment step in Plant D).

The conclusions from this overview of the present treatment technology are:

1. The variability of unit wastewater volume output is very significant and apparently random in nature. It is difficult to maintain the unit water use below 28 dm^3/hog/d, at farms above 10 thousand head.

2. The recommended variability coefficients underestimate the actual conditions. The values estimated during this work were $N_d = 2$, $N_h = 3$ to 5.

3. The concentrations of manure should always be checked against the unit pollutant load from one hog.

4. The combined high-rate chemical and biological treatment system, such as studied here, is capable of producing high quality effluent in cases where quantity is carefully kept at a constant level, within the hydraulic limits of the treatment units. Inadequate equalization; activated sludge vulnerability and bulking tendencies; solids carryover; temperature effects; hydraulic overloading and first of all inadequate maintenance are the causes of poor plant performance.

5. The analysis of the unit processes efficiencies revealed that the high-rate treatment is uneconomical because of power use for pumping, aeration and agitation and chemical costs.

6. Solids removal as primary treatment is essential.

7. Coagulation will have to be removed in favor of plain sedimentation and longer aeration times, due to problems with sludge disposal and high O&M costs.

8. Activated sludge is of bacterial type and quite sensitive to temperature variations.

9. Activated sludge solids carryover, i.e. poor solids capture, are responsible for at least 20 percent of the non-filtered BOD_5.

10. Polishing treatment is essential prior to the stream discharge of piggery effluent. Anaerobic biofiltration yields over 50 percent of $BOD_{5,nf}$ removal.

11. The research needs promulgated by this work are:

a - methods of decreasing unit water demand;
b - introduction of low energy - low rate treatment units;
c - solution of chemical and biological sludge disposal problem (present studies with irrigation of poplars need to be carried for 5 more years);
d - economical recovery of by-products, SCP, gas, and treated wastewater recycle for flushing; and
e - increasing concentration of effluents and methods of economic land application as the final disposal of effluents.

SECTION 5

SAMPLING AND ANALYTICAL METHODS

SAMPLING

Samples for analysis of efficiency of the Vidus type treatment plant performance were collected immediately before and after the unit evaluated, in one-hour intervals, through 72 consecutive hours. The samples were then collected into containers; each contained the interval of one 8 hr shift; the samples were added to containers in quantity proportional to the volume of flow-according to the method described by Oleszkiewicz (174).

The wastes for studies at the departmental laboratory were collected from Plant A, Agrokomplex type farm with 10.5 thousand head capacity: a) raw wastes from the wet well and b) treated wastes for polishing studies, from the final clarifier overflow.

ANALYTICAL METHODS

Organic content was measured by means of 5 day - Biochemical oxygen demand both in filtered ($BOD_{5,f}$) and nonfiltered samples ($BOD_{5,nf}$); by chemical oxygen demand (COD_f and COD_{nf}) and total and soluble organic carbon (TOC and SOC). Due to lab space and time difficulties, a shorter, 10 min COD digestion method was adopted (32, 98); method yielded comparable results constantly 5 percent lower than the two-hours-digestion-COD. The calibration is presented in Figure 13. The same figure (B) gives a correlation between both COD 10 min and 2 hr against total solids (TS) as:

$$COD = 1 + 1.545\ TS\ .\ .\ .\ \ (10^3\ mg\ O_2/dm^3) \qquad (7)$$

used for qualifying outliers in the data pool. All other determinations were

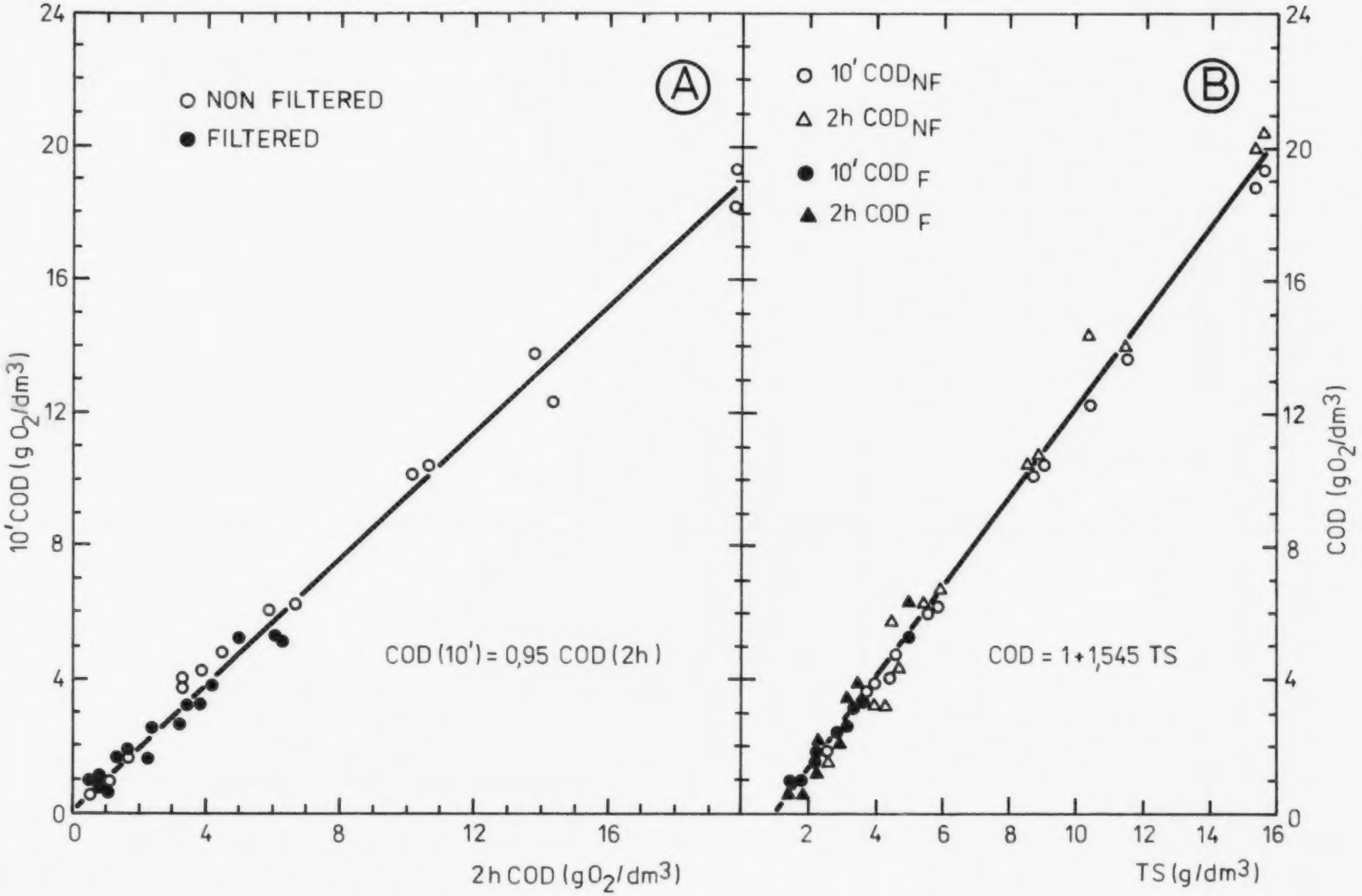

Figure 13. (A) Comparison of 10 minutes and 2h COD digestion; (B) Calibration of COD against total solids - TS.

done according to EPA Methods (31). Additionally, permanganate value of oxygen demand was analyzed according to Polish standards (32) to facilitate an estimate of BOD dilutions.

The total and dissolved solids content were analyzed according to USA ASTM Designation (33), while the determinations of suspended solids for both total and volatile (TSS, VSS) were according to EPA Methods (31).

Nitrogen determinations N-NH_4, N-org., TKN were made according to EPA Methods (31). For the Kjeldahl nitrogen (TKN), a selenium catalyst was used. Modifications according to Polish Standards (34, 35) had to be made for determinations of N-NO_3 and N-NO_2 due to lack of catalists. The samples for nitrates were prepared by filtration with activated carbon through a medium filter paper and coagulation with zinc sulphate in alkaline conditions and then filtered again. Then the sample was neutralized, urea was added (in proportion to N-NO_2 content), acidified with H_2SO_4 and heated for 16 hours. Somewhat different procedures was used for samples where the values of NO_3 were much higher than NO_2, i.e. NO_2 less than 0.1 mg/dm^3.

Other analyses were made in accordance with US EPA Methods or if the manual did not elaborate on a particular analysis, Standard Methods were applied (36). This applied to determination of phosphorus, chlorides, sulfides, sulphates and heavy metals by atomic absorption spectrophotometry.

SECTION 6

PRIMARY AND SECONDARY AEROBIC TREATMENT

SEDIMENTATION

The solids that are entrained in piggery wastes consist of unused fodder, some bedding, urine, feces, large incidental objects, etc. These are usually removed by screening. The openings of 1.0 to 1.5 mm were found to be the best for the vibrating screens. The screening efficiencies were presented in Figure 7 and 10 based on references (26, 28). This section is aimed at evaluating the sedimentation feasibility as a sole pretreatment to further biotreatment. Optimum settling time will be selected and effects of primary aeration (practiced now in some full scale plants) will be evaluated.

Methods

Settling tests were performed on site at Farm A. The wastewater was subjected to the normal wet well mixing and pumping, and dynamic screening through 1.5 x 1.5 mm open screens. The tests were run in a series of 1 dm^3 cylinders - 45 cm high. The samples were collected by pipette from a depth of 25 cm below surface at selected time intervals: 1 min, 3 min, 5 min, 10 min, 0.5 hr, 1 hr, 2 hr, 3 hr, 24 hr, and 38 hr. One cylinder represented one sampling interval. The efficiency was measured by COD, permangate values COD and $BOD_{5,nf}$ analyses.

Results and Discussions

Most of the settling tests had evidenced very rapid initial solids removal in the first few minutes followed by gradual settling of finer solids, which was practically completed within 90 to 120 min. The difficulties in comparing the relative rate of settling led to the development of the log-log plot of effluent suspended solids, BOD and COD versus time, according to the equation:

$$S_t = S_1/t^a \qquad (8)$$

where S_t, S_1 are respectively, effluent concentration after time - t, and concentration after t = 1 min; t = settling time and a = the slope of the settling curve representative of rate at which pollutant removal occurs. The value of S_1 is the intersect of the curve with the ordinate at t = 1 min, a convenient time to record the initial or immediate removal.

Typical removals of TSS and organics are presented in Figure 14 which shows effects of preaeration on the final TSS and BOD and COD concentrations.

The TSS removals, calculated as $(1 - S_t/S_o)$, indicate that the removal is the most efficient in the first 30 minutes of the process and averages 75 percent. A one hour settling results usually in an average 78 percent solids removal, while an additional hour yields an increase of only 3 percent up to N = 81 percent. Further sedimentation, beyond the two-hour limit yields only 1 percent increase and at 3 hr, N = 82 percent curve 1 shown in Figure 15.

The removal of COD and BOD_5, Figure 15, confirms the above conclusion. The average organics removals curve forms platteau after two hours of settling.

Primary aeration was tried as a method of enhancing solids removal. Figures 14 and 15 indicate the effects of 0.5 hr aeration and a prolonged 19 hr preaeration. It was found that in both cases, the primary aeration has increased the solids removal by some 4 percent. A more pronounced effect was evidenced in organics removals which were increased by over 10 percent. The comparison indicates that primary aeration, of very short duration, should be employed, e.g. as a method for mixing the wet-well contents.

Summary

Most of the imported piggery wastewater treatment plants apply screening and chemical coagulation as primary treatment. This research has shown that plain sedimentation, after fine screening 0.5 to 1 mm, which results in the directly reusable by-product can be effectively substituted for expensive alum coagulation. Figure 15-B illustrates statistical analysis of two-hour settling tests conducted at other plants with annual production ranging from 14 to 35 thousand hogs. The tests yielded an average decrease of total COD

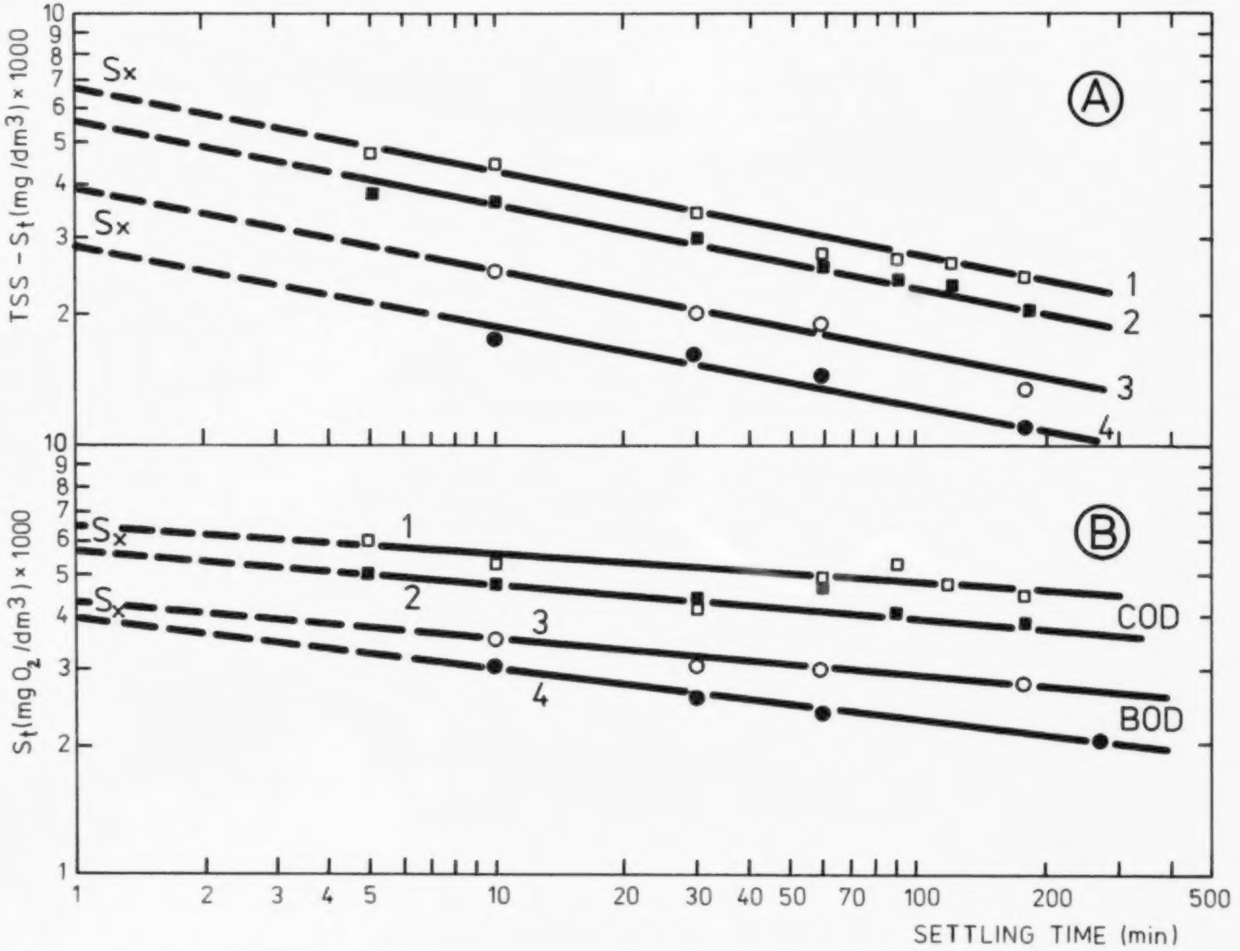

Figure 14. Effects of preaeration on removal of: (A) Suspended solids; (B) Organics; 1 - raw, fresh waste and 2 - after 0.5h aeration on 24.IV.78; 3 - raw, fresh waste and 4 - after 19h preaeration on 25.V.79.

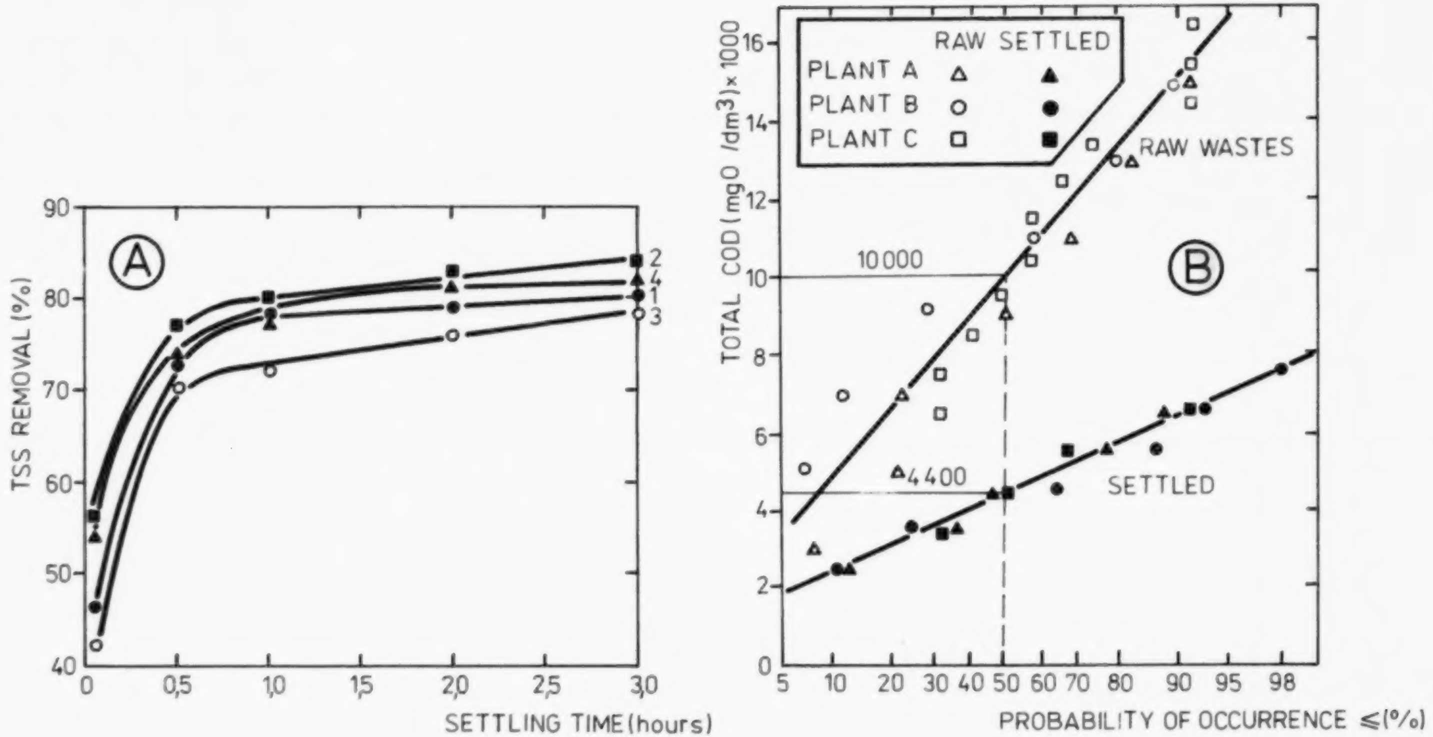

Figure 15. (A) Settling curves for Plant A raw wastewaters: line 1 - $S_o = 12{,}500$ mg TSS/dm^3, 2 - aerated $S_o = 12{,}700$ mg TSS/dm^3, line 3 - $S_o = 6{,}770$ mg TSS/dm^3, 4 - aerated $S_o = 6{,}230$ mg/dm^3; (B) COD$_{nf}$ removal efficiency during settling of three plants wastewaters.

down to about 4400 mg/dm^3, i.e. a removal of some 52 to 59 percent, which compares well with the results of this study.

Full-scale studies with alum coagulation of very diluted wastes yielded the following removals: COD_{nf} - 62 percent; $BOD_{5,nf}$ - 39 percent; $BOD_{5,f}$ - 26 percent; and TSS - 82 percent. One has to take into account the fact that diluted wastewaters yield lower removals (26), however, it is evident that coagulation does not add that much in terms of additional removals. A study at Farm D, 28 thousand head, yielded 65 percent COD removal in coagulation of screened, more concentrated wastes.

The summary of findings is as follows:

1. In spite of attaining removals lower than with alum coagulation, plain sedimentation appears to be the most economical method of primary treatment, where sludge disposal is concerned, leading to average removals expected: COD_{nf} - 55 percent; $BOD_{5,nf}$ - 35 percent; and TSS - 80 percent.
2. Primary advantage of sedimentation is the small volume of sludge and its good dewaterability when compared with chemical sludge.
3. Preaeration should precede settling and could be effectively combined with mixing of wet wells, presently turbine mixers are used that result in particle shearing and decrease the settling efficiency, and can yield up to a 5 percent improvement of solids removal.
4. Short, half-hour preaeration is sufficient to yield a 10 percent improvement in organics removal.
5. The optimum settling time for piggery wastes, in quiescent, laboratory conditions, is two hours. Longer times yield only negligible improvements in removal efficiencies.
6. A novel method of presenting settling data was employed which allows for comparison of settling rates for various effluents based on rate coefficient, "a," in the equation ($S_t = S_1/t^a$).

COAGULATION OF PIGGERY WASTEWATERS

Screened piggery wastewaters contain unusually high amounts of non-settling suspended solids and colloidal matter. Majority of piggery wastes treatment plants in Poland use alum coagulation as the primary treatment step, prior to the subsequent biological processes. Due to the license recommendations and the lack of in-depth coagulant type and dose selection studies, it is universally practiced to apply the alum dose of at least 1 kg/m^3. Operators use larger doses when stronger raw wastes are received at the plant. Under these circumstances, the cost of coagulant is a large component of the operating costs (over 15 percent), while the volume of sludge, reported at some plants over 30 percent of the daily wastewater flow results in the most formidable ultimate disposal problem at the plant.

The practice of chemical sludge volume reduction and ultimate disposal is in the early stages of development (30), particularly for the relatively low volumes encountered at hog farms. Nevertheless, attempts have been made to dewater the sludge by mechanical centrifuging. Favorable results were obtained only at very high sludge conditioning polymer doses (29).

The present studies were undertaken to find the optimum alum coagulant dose at varying wastewater quality and to evaluate the feasibility of using other coagulants that are less expensive and that will produce lower volume of sludge more amenable to air dyring or other simple dewatering means.

The second part of this work, dealing with comparison of two parallel systems: coagulation followed by activated sludge and activated sludge followed by coagulation was conducted in order to optimize coagulant cost and the total volume of produced sludge.

Materials and Methods

Routine 1 dm^3 jar test procedure was used. Rapid mixing lasted 3 min at 80 rpm, and slow mixing lasted 20 min at 20 rpm. A two-hour settling preceded supernatant sample collection and determination of sludge volume.

The efficiency of coagulation was determined as a function of dose D, in terms of optimal dose D_{opt}; effects of various factors were also analyzed such as the age of pig wastes and the use of Pollena JK disinfectant. The conclusions were drawn based on a relationship:

$$(S_o - S_e) = D.f(S_o) \quad (9)$$

where S_o, S_e are initial and effluent wastes concentration; (COD and TSS were used); $f(S_o)$ as a function of initial concentration.

Results

Full scale results at Plant A obtained at the varying dose of 1,000 to 1,300 mg/dm^3 of $H_2(SO_4)_3$ showed COD_{nf} removals to be 55 to 85 percent.

The laboratory jar tests were conducted at random since 1978 in order to get enough data for statistical analysis. The raw wastes COD_{nf} concentrations varied from 3,800 to 18,000 mg O_2/dm^3. Several correlations were analyzed. The basic graph of S_e versus D was interpreted for an optimum dose D_{opt} as in Figure 16-B. The value of S_e at D_{opt}, denoted S_{opt} was compared against the values of S_e after 2 hr settling, with filtered sample concentration, and with the S_e at D = 1,000 mg/dm^3 (Figure 17-A).

The analysis has been performed graphically and in tabular form. Graphical analysis showed that there are two distinct segments of the dose-effects curve. The first part, at doses below D_{opt} is linear and may be expressed as S_e/S_o = 1 - a.D where a = (7 to 9) 10^{-4} and D is dose in mg/dm^3. The overall curve can be expressed as an exponential curve $S_e/S_o = D^{-a}$ where a = 0.25 to 0.35. The correlations were seldom satisfactory, and it was difficult to evaluate the effects of increased disinfectant use or prolonged storage of manure in the farm sewer system. The results indicate that coagulation is the most efficient on fresh wastes, preaerated, and with the minimum amount of Pollena JK disinfectant used.

Figure 17 illustrates the effects of an averaged optimized dose of alum coagulant (D_{opt}=390 mg/dm^3 of $Al_2(SO_4)_3 \cdot 18 H_2O$) compared with average (of 6 runs) effects of 2 hours and 4 hours sedimentation and the effect of coagulant dose up to the assymptote (usually D=1,300 to 1,400 mg/dm^3) and filtration. Comparing the effects of practiced design alum dose of 1,000 mg/dm^3 with effects of D_{opt} and the costs of sludge disposal which are over three times higher for the design dose, it is evident that increased removal in the overall plant efficiency analysis is offset by coagulant and sludge disposal costs.

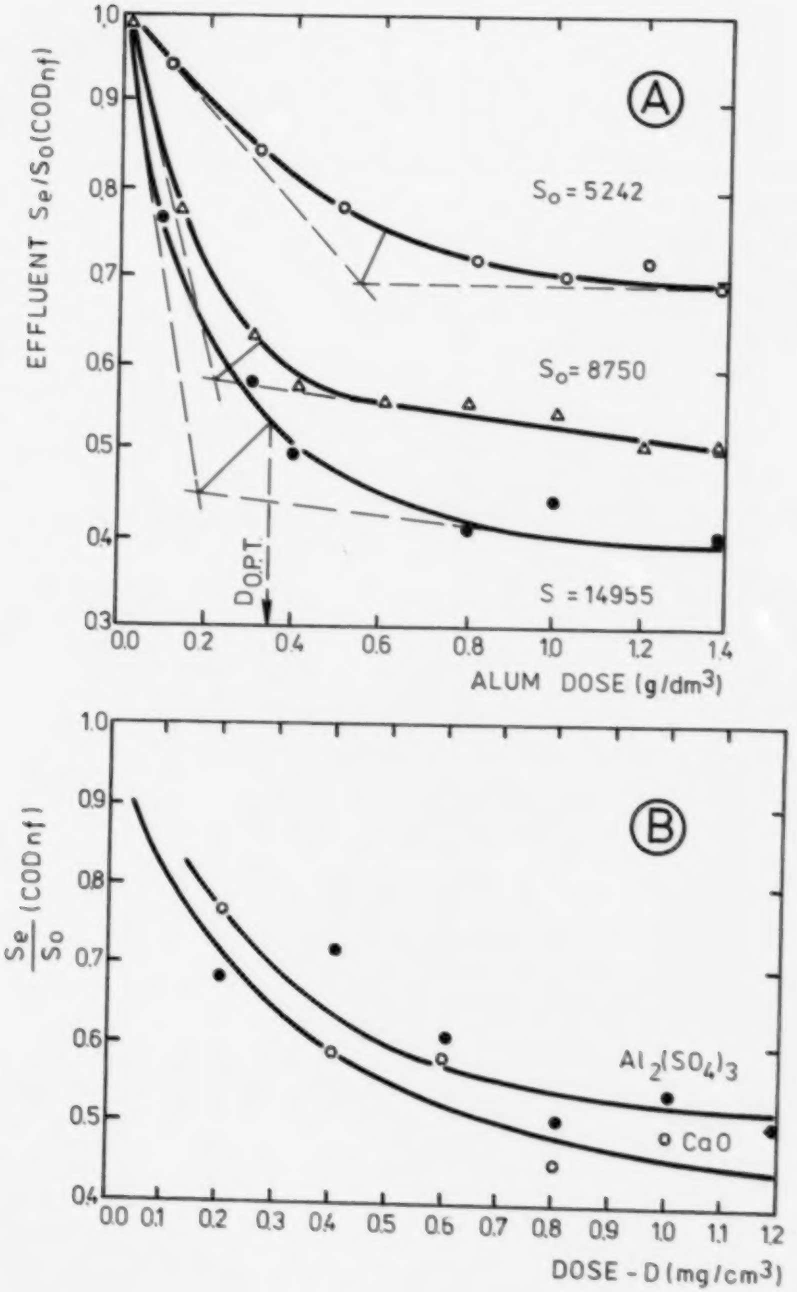

Figure 16. Effects of coagulation: (A) Waste stored for two days - 1978, 1979 data; (B) Fresh wastes - 1980 data.

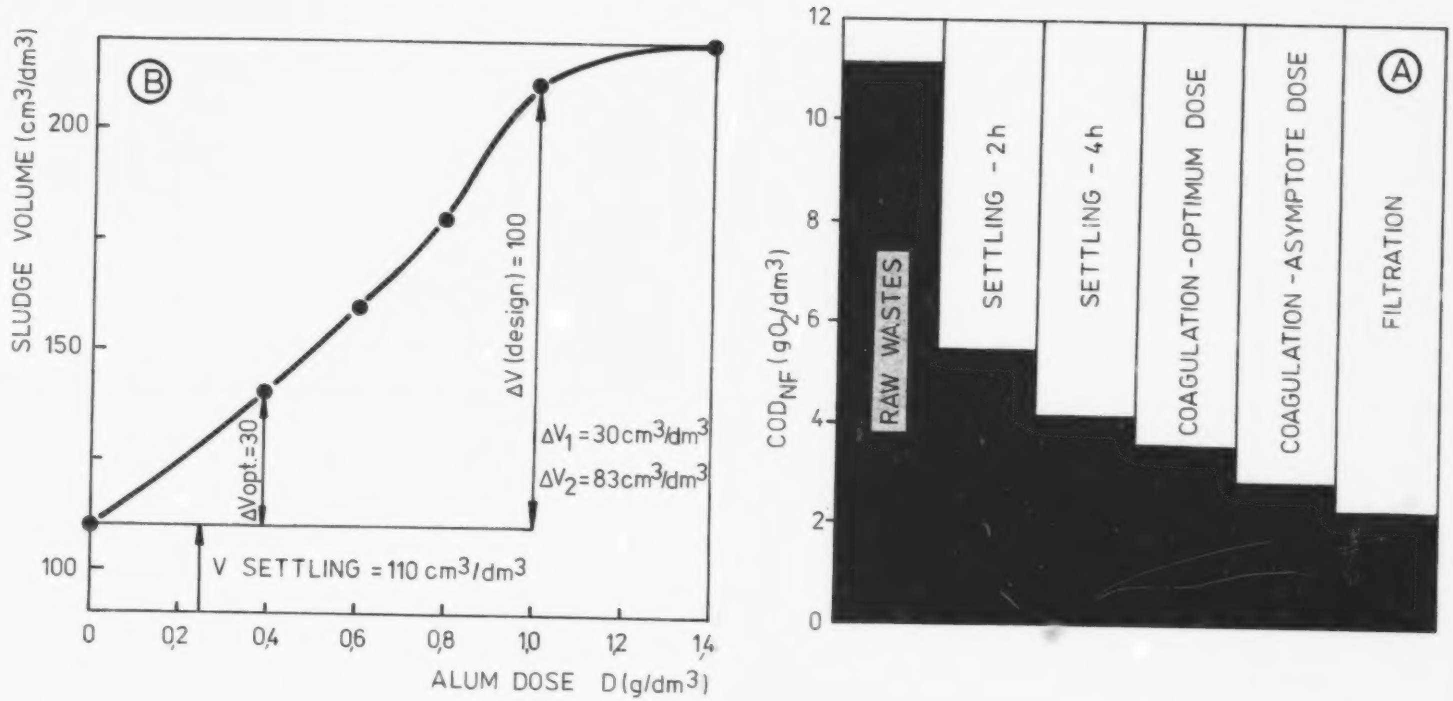

Figure 17. Comparison of coagulation effects with settling: (A) Efficiency of COD_{nf} removal by various processes; (B) Sludge volume at various alum doses.

The analysis of the data gathered from 1978 to 1979 showed that:

The ratio of effluent COD concentration at alum dose 1,000 mg/dm^3 to concentration at an optimum dose - S_{opt} varied:

$$S_e(D=1000)/S_{opt} = 0.75 - 0.90 \qquad (10)$$

the ratio of S_{opt} to the filtered COD (soluble)/:

$$S_{opt}/S_f = 0.60 - 0.75; \qquad (11)$$

the range of values of the removal by coagulation with an optimum dose over the effects of two hours sedimentation:

$$\frac{S_e(\text{sedim.}) - S_{opt}}{S_e(\text{sedim.})} = 0 - 35\% \text{ (COD)} \qquad (12)$$

with a mean of 10 percent.

Conclusions

The presently used dose of alum, 1000 mg/dm^3, is too high from the standpoint of technological and economic efficiency. The optimum dose of alum is 390 mg/dm^3 in ideal laboratory conditions. The sludge volume at D_{opt} is 0.03 m^3/m^3 (3 percent) of wastewaters. Increase of the alum dose beyond D_{opt} results in only 15 percent increase of COD removal efficiency and over 300 percent increase in the resulting sludge volume. The alternative; sedimentation, yields removals of COD some 10 percent smaller than the optimum dose coagulation effects; the sludge, however, has good dewatering characteristics.

The dose-response curves were analyzed by means of tangents to the respective ends of the curve in order to find D_{opt}. Little correlation was found between the initial concentration S_o and the optimum dose and the coagulation efficiency. The incidental use of disinfectants had detrimental effects on organics removal.

In existing systems that use coagulation, alternative coagulants should be researched. Lime proved equally effective in jar tests in approximately 50 percent of cases. At higher influent COD concentrations, the alum was by far superior.

ACTIVATED SLUDGE - SECONDARY TREATMENT

The activated sludge process has been used with various modifications to treat raw pig wastes for over two decades. The most popular systems for concentrated wastewaters are under-the-slatted-floor oxidation ditches (37) or separated oxidation ditches (38), however, completely mixed reactors have also been used (39). The data available on dilute effluent biotreatment is ambiguous and lacks the full understanding of kinetics and reasons for the bulking tendencies (25, 40). The present studies are aimed at testing the reasons for better unit efficiencies and sludge yields experienced in activated sludge treatment of primarily coagulated dilute wastes from Farm A. The tests were conducted in laboratory units as in Figure 18.

Pretreatment by Coagulation

Two runs of batch tests were made. The run consisted of setting six parallel activated sludge tanks to which enough activated sludge, acclimated to chemically pretreated wastes, was added to attain $X_v = 2.5$ to $3.5\ g/dm^3$. Equal 1 dm^3 volumes of wastes were treated in a jar test apparatus with alum dose of 0, 100, 200, 400, 800, and 1,200 mg/dm^3. The effluent was fed into the activated sludge tanks and aerated for 24 hours. Samples were collected at 2, 4, 6, 8, 10, 12, and 24 hr in the first run and at 3, 6, 9, 12, and 24 hr in the second run. The removal rates (K) for each individual unit were calculated from:

$$S_e/S_o = \exp(-Kt) \tag{13}$$

and expressed in (1/d). The results were plotted in K versus dose D to arrive at an optimized coagulant dose. Figure 19 illustrates the selection of an optimum dose as 400 mg/dm^3, the value coincidental with the results of the coagulation optimization tests described in the previous chapter (the D_{opt} - was equal to 390 mg/dm^3). The second batch yielded different results, indicating that beneficial effects of coagulation as primary treatment may not be pronounced at all, at times. Due to the fact that it was not possible to monitor the addition of disinfectants at the farm, it is still unclear why such fluctuation of removals was attained.

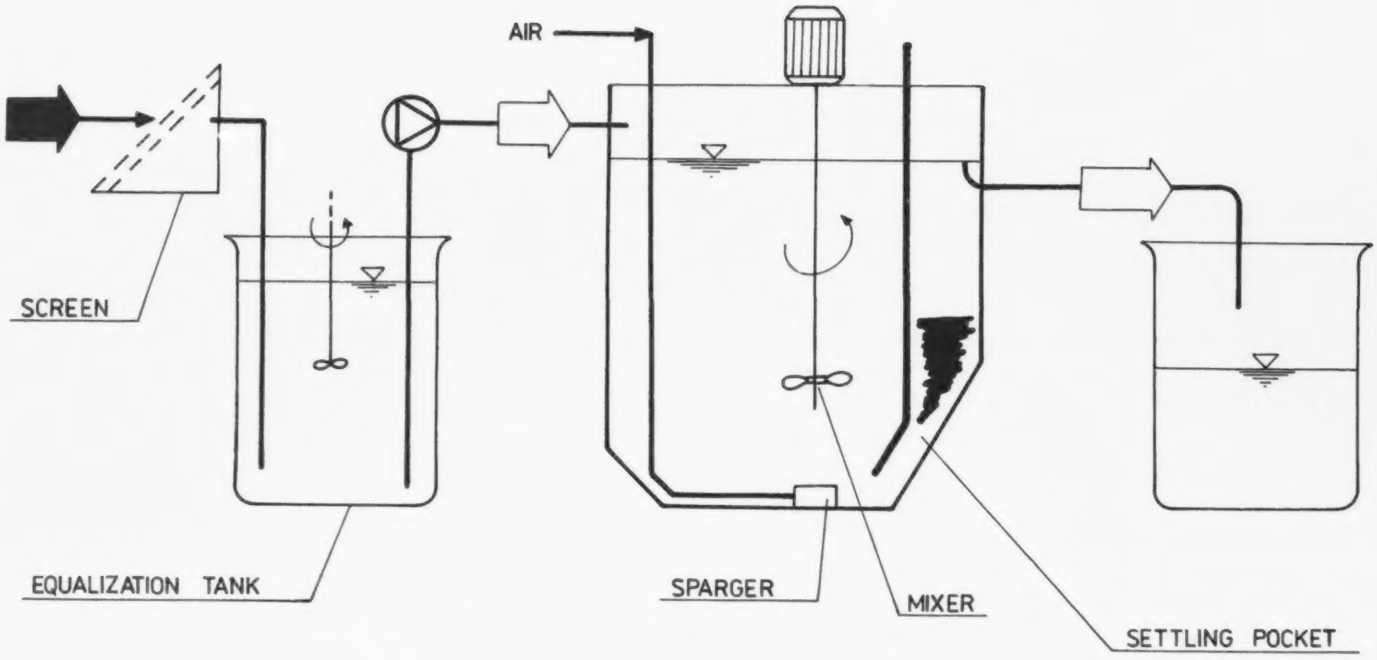
AIR
SCREEN
EQUALIZATION TANK
SPARGER
MIXER
SETTLING POCKET

Figure 18. Layout of experimental activated sludge set-up.

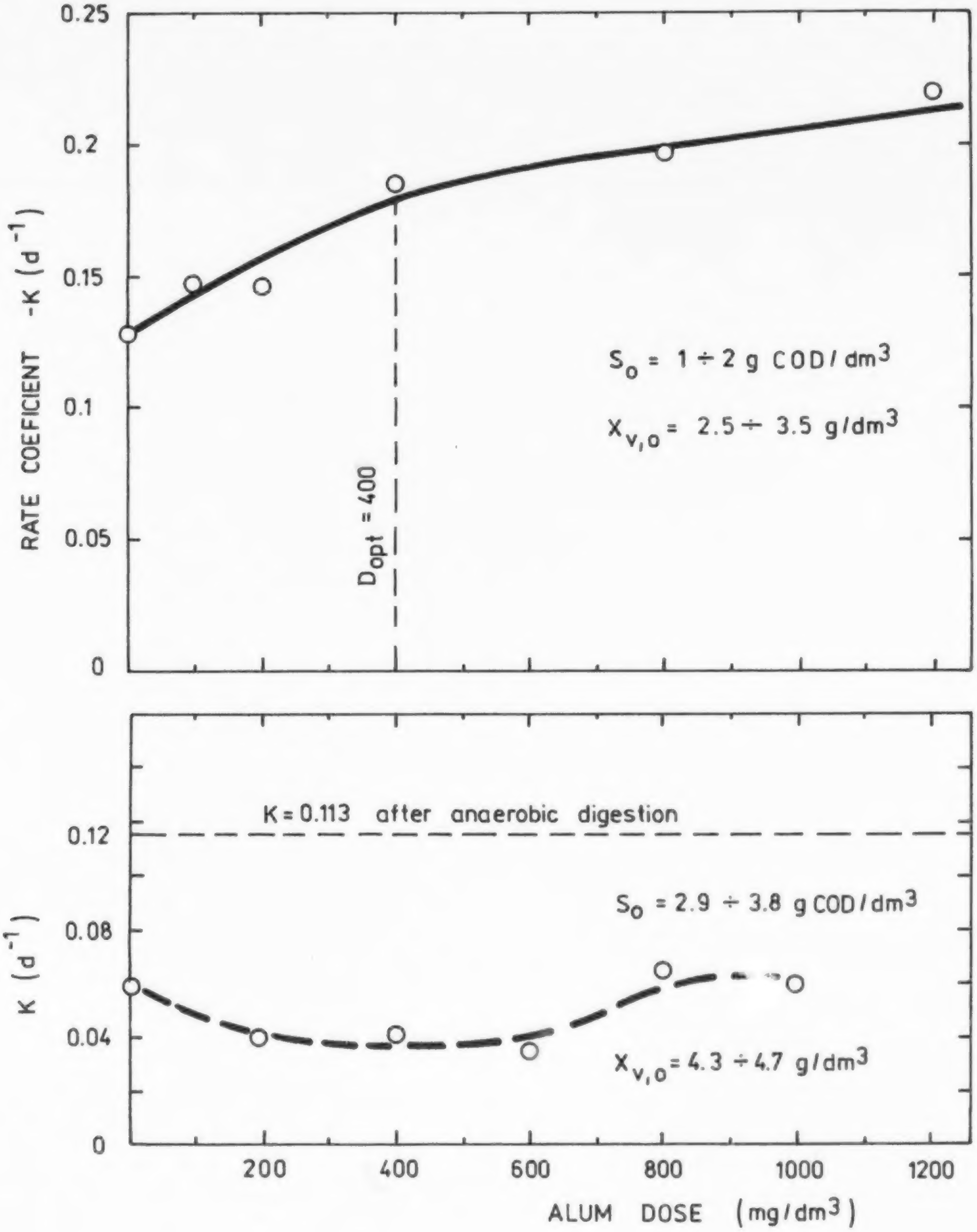

Figure 19. Effects of coagulation on COD removal rate in (batch) activated sludge.

Continuous Studies - Pretreatment by Settling

Continuous studies (Figure 18) comprised of two systems: I) alum coagulation - activated sludge, and II) settling - activated sludge - alum coagulation. In the first system a massive dose of alum was used: 1200 to 1400 mg/dm^3. In the second system the coagulant dose was 200 to 250 mg/dm^3 as higher doses yielded nothing in terms of additional removal. The tests were run on Farm A wastewaters in 1978, prior to modification, thus, the influent concentrations were very low. The average raw wastes COD$_f$ was 3870 mg O_2/dm^3 (SYSTEM I) and 3130 mg O_2/dm^3 (SYSTEM II). The aeration time was varied from 18.5 to 28.2 hr and activated sludge loading F/M from 0.4 to 1.4 kg COD/kg MLSS/day. In order to remove the difficulties in maintaining small flow-rates through aeration tanks, varying volumes were used. Each test consisted of three parallel units with volumes 11.4, 17.9, and 34.4 dm^3. Activated sludge concentration was kept at 2.2 to 3.5 g/dm^3. The results are summarized in Figure 20. Part A depicts the soluble COD removal across the aeration tank only indicating only five percent higher removal efficiency, at the preferred F/M=0.5 kg COD/kg MLSS/d for the first system, i.e. coagulation - activated sludge.

Sludge growth kinetics study has shown that SYSTEM I had sludge synthesis coefficient a=0.53 and sludge endogeneous respiration coefficient b=0.03 d^{-1}. The coefficients for SYSTEM II were a=0.40 and b=0.008 d^{-1}.

The analysis of performance data for the whole treatment trains reveals that at 24 hr aeration time, SYSTEM I efficiency is approximately 5 to 6 percent higher than the COD removal efficiency of SYSTEM II, settling-activated sludecoagulation. Figure 20-B shows that the overall sludge production in SYSTEM I rises by over 120 percent above the SYSTEM II. The data is verified by the results of settling tests (Figure 17).

Biological Comparison of Various Pretreatment Methods

Three parallel batch activated sludge units were observed during 24 hr aeration. Tank 1 treated effluent from 2 hr sedimentation, tank 2 from anaerobic digestion in continuous flow contact digestors with sludge recycle, and tank 3 treated effluent from coagulation with 1 g/dm^3-alum.

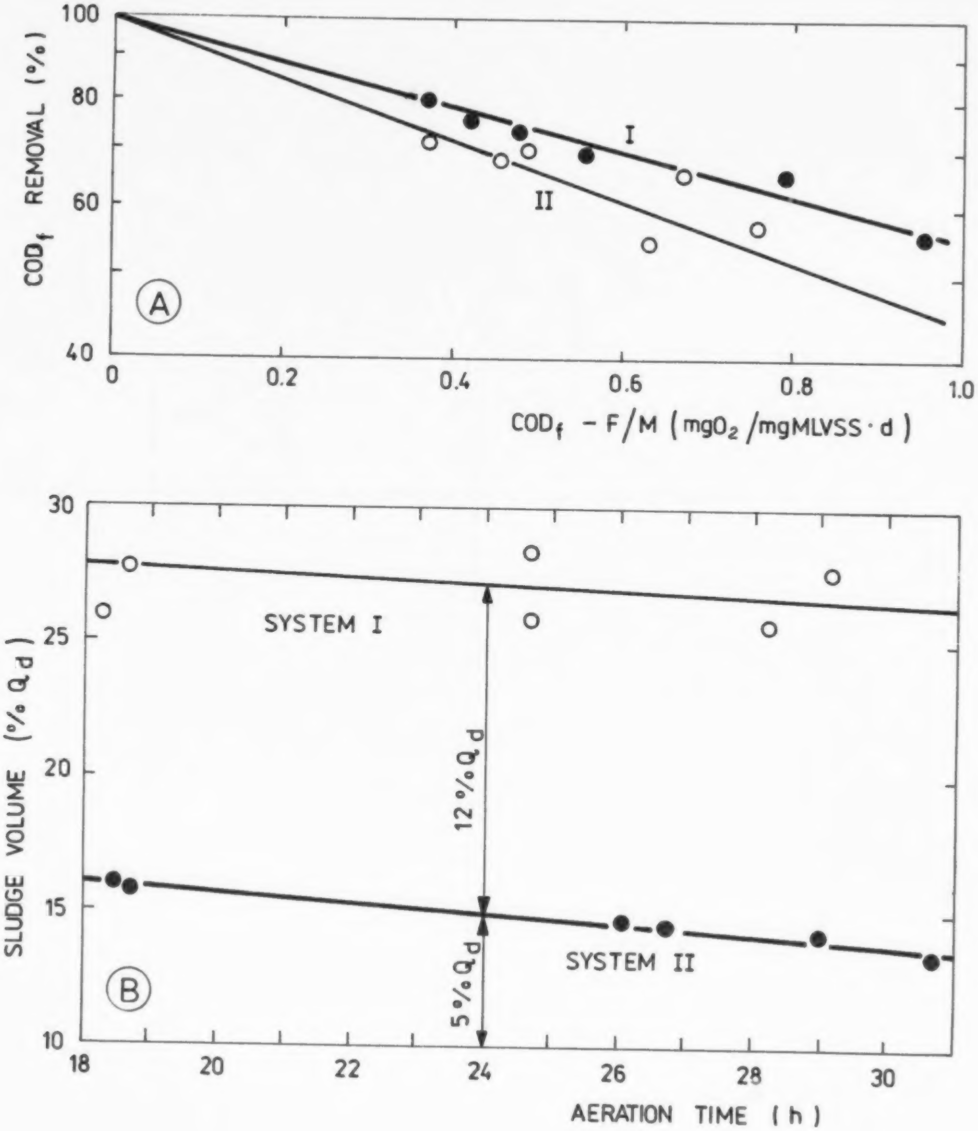

Figure 20. Continuous activated sludge treatment of system (I) C-AS and (I) S-AS-C: (A) COD$_f$ removal across the aeration tank; (B) Overall sludge produced in the whole treatment train.

Methods--

Activated sludge before being fed to the batch reactors was acclimated to the wastes under study, e.g. tank 3 activated sludge was grown on substrate subject to alum coagulation. Hydrobiological analysis encompassed microscope studies at t=0, 12 and 24 hr. The method used (99) was confined to description of flocs, characterization of species and evaluation of the empty spaces between flocs. Photographs made are reproduced at 40 x magnification. The activated sludge activity test TTC (100) supplemented biological analysis.

TABLE 4. COMPARISON OF THREE PRETREATMENT METHODS - BATCH ACTIVATED SLUDGE

	Settling Tank 1	Anaerobic Tank 2	Chemical Tank 3
Influent COD - S_o mg O_2/dm^3	3,760	2,700	3,180
Sludge content - X_v mg VSS/dm^3	3,720	6,424	4,301
F/M mg COD/mg VSS	1.01	0.42	0.74
Sludge growth g.VSS/g BOD_{rem}	0.55	0.78	0.42
Removal rate - K (h^{-1})	0.070	0.09	0.062
TTC (μ mole TF/g VS) t = 0h	0.085	0.045	0.032
t = 24h	0.019	0.010	0.023
Cilliata sp. (Opercularia) fraction of the total no. of organisms (%)			
TIME: 0h	76.8	67.7	35.1
12h	84.6	70.1	49.3
24h	50.8	91.9	72.1
Visual analysis of floc type and open spaces from photographs.	(--)	(++)	(+-)

The physical-chemical parameters, particularly the shape of the removal curve and the value of the removal rate coefficient indicate that anaerobic pretreatment is better than the two remaining methods. The anaerobic-aerobic system exhibits also the best sludge growth and the highest proportion of the protozoans, Cilliata. The presence of these species is regarded traditionally as the bioindication of the healthy state of the biota (101, 102).

Visual observation has also been performed. The photographs in Figure 21 illustrate on the left-hand column the sludge (40x) at t=0h, i.e. previously

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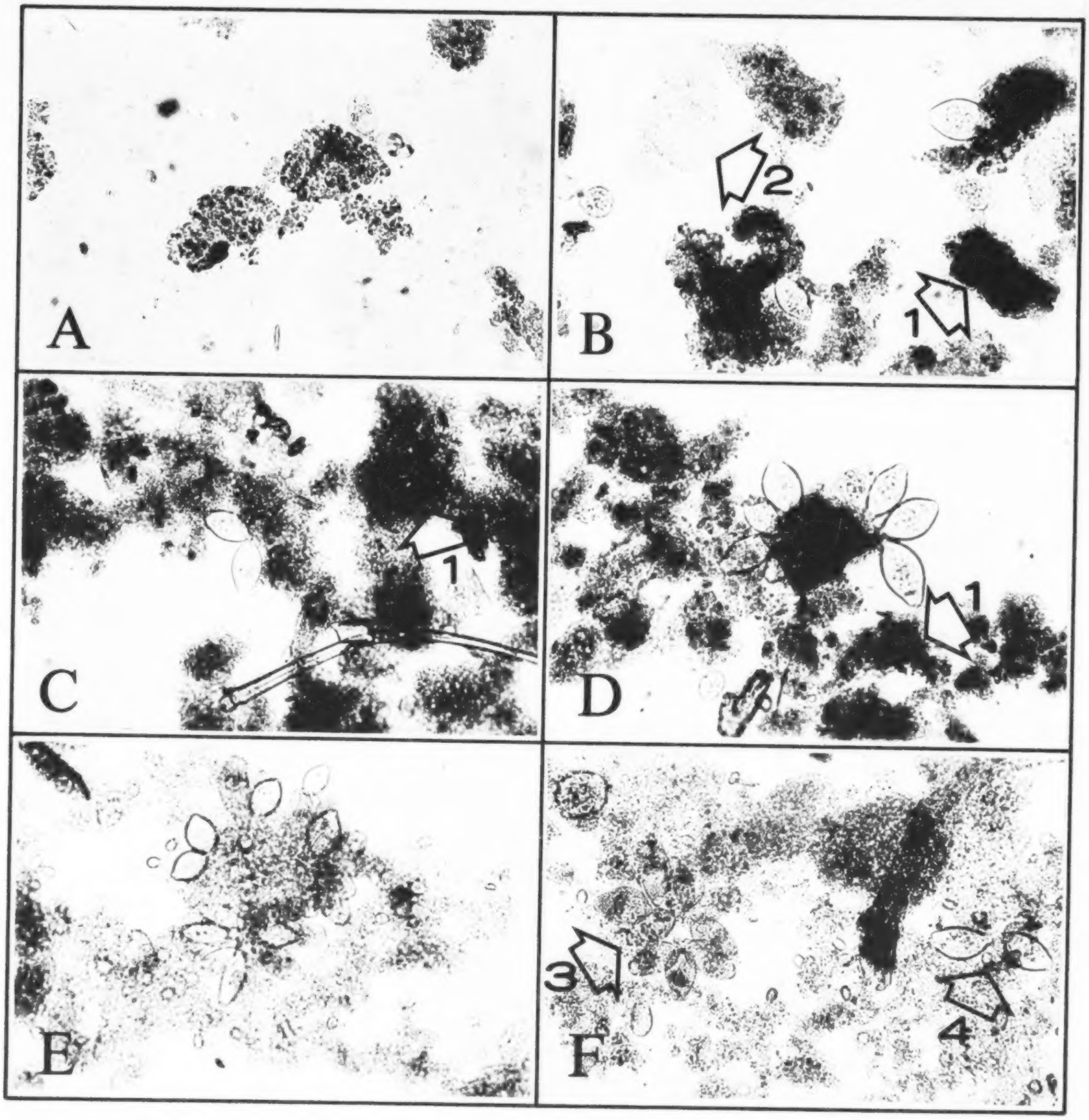


Figure 21. Microscopic picture (40 X) of activated sludge: at t = 0h tanks 1, 2 and 3 are respectively A, C, and E; at t = 24h tanks 1, 2 and 3 are respectively B, D, and F: 1) agglomerated flocs, 2) Zooglea uva Kolkw., 3) Opercularia sp. - poor physical condition colony, 4) Opercularia sp. - two individuals colony of good condition.

acclimated to the wastes; at right-hand column the same sludge after 24 hr batch aeration.

The tank 1 sludge at t=0 had compact flocs and loose bacteria clustering the free spaces. After 24 hr, the quality of flocs deteriorated significantly, the flocs were still compacted, but they appeared as if coagulated with the increased number of zoogleal agglomerations that occupied close to 50 percent of the empty spaces were cleared of single bacteria.

The tank 2 sludge, after anaerobic pretreatment, exhibited little negative changes during 24 hours. The flocs were much better formed than in tank 1 or 3, looked very fluffy and well multi-layered. The agglomerated or compacted flocs, i.e. very dark points evident in the photographs (a negative symptom) have intensified in 24 hr, however, the empty spaces cleared and the overall picture is superior to the parallel systems.

In tank 3 the flocks were formed spaciously, however, the appearance was similar to activated sludge after prolonged aerobic stabilization, both at 0 and 24 hr. The flocks were not multi-layered as in tank 2 and were quite dispersed with very weakly defined empty spaces. The initial dehydrogenase activity (TTC) was the lowest of all three for tank 3.

Conclusions--

Pretreatment by settling only yielded sludge (in tank 1) which lacked full development, was compacted into agglomerations, thus not exposed to substrate. Problems may be expected in full scale operation.

The activated sludge in tank 2 had the most satisfactory appearance, was well formed in multilayered flocs, and had good bacteriological and protozoological characteristics. Anaerobic pretreatment has produced the most appropriate effluent for further activated sludge treatment.

Pretreatment by coagulation results in the development of loosely formed dispersed sludge, which appears the most vulnerable of all three to minor changes in the technological regime.

TABLE 5. ACTIVATED SLUDGE POLISHING TREATMENT OF EFFLUENT FROM THE VIDUS TYPE PLANT AT FARM A

Parameter	Units	Series I				Series II			
		1	2	3	4	1	2	3	4
Aeration tank vol.	dm^3	5.7	11.4	17.9	34.4	5.7	11.4	17.9	34.4
Aeration time - t	hours	28	41	55	79	33	37	57	62
F/M BOD_5	g $O_2/g/d$	0.47	0.29	0.19	0.03	0.15	0.09	0.05	0.02
Influent $S_{o,f}$	mg O_2/dm^3								
COD		142	138	142	138	110	110	110	110
BOD_5		86	76	64	78	44	44	44	44
Effluent $S_{e,f}$	mg O_2/dm^3								
COD		84	72	60	51	66	62	57	55
BOD_5		44	29	20	13	22	20	17	15
MLVSS - X_v	mg/dm^3	170	170	190	780	210	220	370	850
Removal rate k	d^{-1}								
COD		0.494	0.432	0.445	0.091	0.253	0.251	0.116	0.05
BOD_5									
Removal efficiency	%								
COD		40	48	58	63	40	44	48	50
BOD		49	62	73	83	50	55	61	66

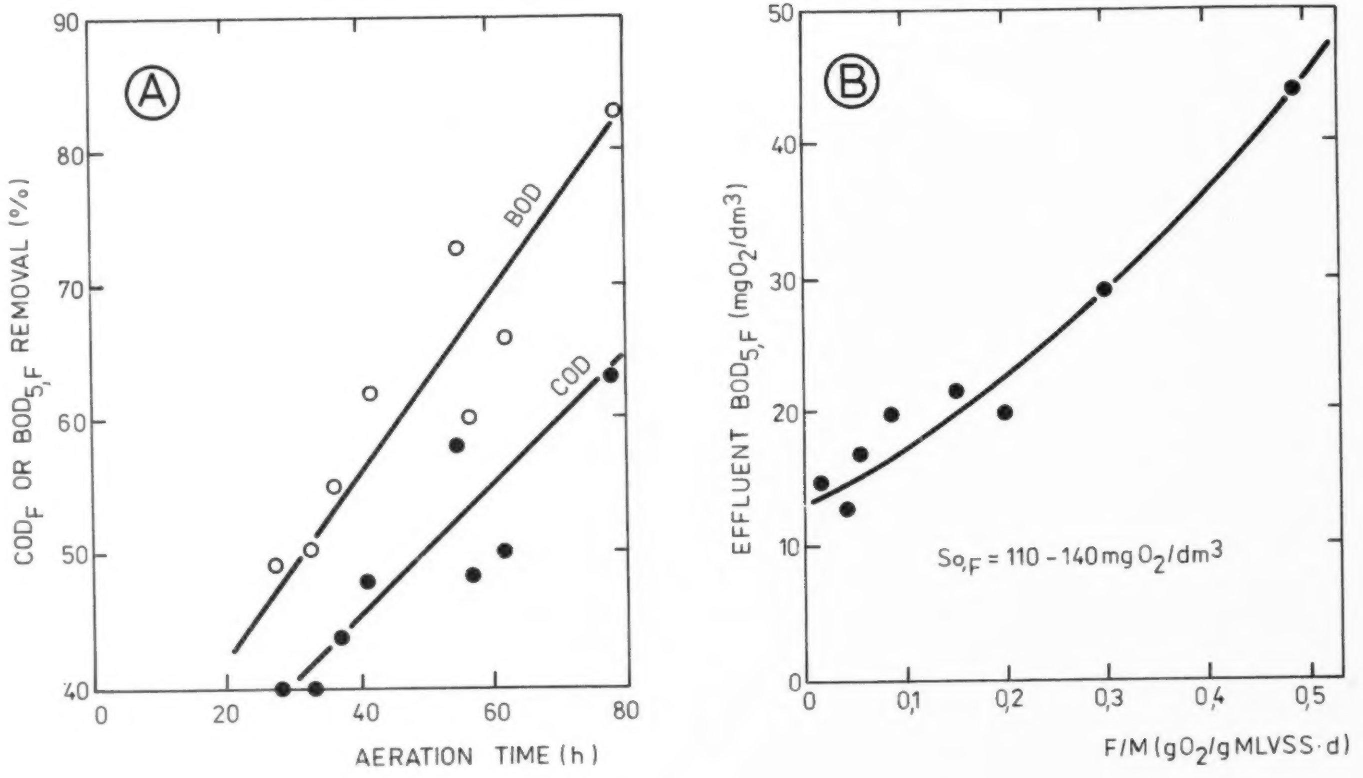


Figure 22. Continuous extended aeration of activated sludge effluent from Farm A: (A) Efficiency as affected by aeration time; (B) Effluent quality versus sludge loading in the test units.

Relatively low removals at 24 hr detention time, equal approximately to 45 percent $BOD_{5,f}$ and 40 percent COD_f, when analyzed from the standpoint of costs of aeration prove the process to be uneconomical.

It was then assumed that intermittent aeration, cutting the aeration costs by over 50 percent, with the simultaneous increase of the aeration volume should yield similar or better results. Intermittent aeration was practiced in two parallel runs, 11 hr/d while the remaining 13 hr, the MLSS were allowed to settle. The data is presented in Table 6.

The kinetic constants were calculated based on the standard kinetic model, described before in the text, $k.S_e/S_o = S_r/X_v.t$.

TABLE 6. COMPARISON OF INTERMITTENT AERATION IN POLISHING ACTIVATED SLUDGE TREATMENT OF BIOLOGICAL EFFLUENT

Tank No. Volume	Aeration Time hour/day	Retention hours	F/M kg BOD_5/kg MLSS/d	BOD_5 Removal Percent
Tank 1 11.4 dm^3	24 hr/d	37	0.09	55
	11 hr/d	37	0.09	50
Tank 2 11.9 dm^3	24 hr/d	57	0.05	61
	11 hr/d	57	0.05	57

Note: Influent COD = 110 mg O_2/dm^3, BOD_5 = 44 mg O_2/dm^3
MLSS = 140 - 230 mg/dm^3

Conclusion

Relatively low values of effluent BOD_5 and COD may be attained in polishing treatment with activated sludge, however, prolonged aeration times make the economic efficiency questionable. One feasible solution would be to use deep facultative lagoons, aerated at a low power level or a completely mixed lagoon, with a settling compartment, aerated intermittently. In rural circumstances the costs of earthen tanks would not be high and the use of interrupted aeration would result in low power consumption and extensive denitrification.

A significant portion of the BOD and COD in these polishing tests was of nitrogeneous origin, as most of the carbon was removed easily in the first biological stage. Based on these studies, low-energy-input aerobic-anoxic (i.e. not strictly anaerobic) or a facultative system is recommended as a polishing system for the biological effluents from the high rate full scale plants.

ALGAL TREATMENT SYSTEMS

Introduction

Full scale algal systems have so far been applied only in regions where there was adequate land area and sunlight, reasonable uniform warm water temperatures, and when there was a demand to utilize the grown biomass while the harvesting methods were economically acceptable.

Large scale demonstration plant on algal (Chlorella vulg.) treatment of nitrogeneous factory wastes in Poland has demonstrated that problems in this region are: low temperatures and high costs of extracted protein about equal to the price of meat protein (41, 42, 103).

The major regular traits of all so far conducted experiments were well described by Goldman (43) as follows:

1. light conversion is less than 5 percent;
2. short-term effects, in idealized lab conditions, yield the (limit) maximum growth rates of 30 to 40 $g.DM/m^2/day$;
3. long-term effects are much lower and seldom exceed 15 to 24 $g\ DM/m^2/$ day (periods of 1 to 3 months);
4. there were no reported cases of pure monoculture growth for an extended period of time;
5. the usually stray cultures, dominating after some time, were Scenedesmus, Chlorella or Micractinium; and
6. temperature is of smaller significance than light intensity.

The studies reported so far on piggery effluents treatment in algal systems yield little more insight. The batch work of Rogiński (44) on filtered wastewaters has suggested the need for immediate dilution of piggery effluents, and was quite optimistic. These laboratory shaker experiments yielded 0.3 to 2 g dry matter (DM)/dm^3/day.

The experiments in Israel (45) have shown that ponds enriched with pig wastes evidenced an increased fish production from 10 up to 30 kg/ha/day, due to the increased plankton content by 100 to 1000 times, as compared to ponds without fertilization. The plankton had 45 to 55 percent of crude protein.

The field studies in Ghent by de Pauw (46) on significantly diluted raw pig wastes have shown yields 0 to 10 g DM/m^2/day depending on temperature and solar radiation. The dry matter, i.e. total solids content was maintained at 30 g/m^2, i.e. 200 mg DM/dm^3 varying as 30 to 220 mg DM/dm^3. In the greenhouse-winter conditions these studies have proved yields of 1 to 3 g DM/m^2/d while average summer yields were 4.8 g DM/m^2/d for Chlorella and 9.2 g DM/m^2/d for Scenedesmus. The optimum retention time was 2 to 8 days depending on light intensity which varied as 43 to 144 cal/cm^2/d. Nutrients conversion rates or biomass production was Y(N)=10 g DM/g N and Y(P)=60 g DM/g P.

The laboratory studies in high temperatures (37°C) were reported by Boersma, et al. (47) to give very high yields depending on dilution of pig wastes and the resulting nitrogen content. At 63 mg N/dm^3, the yield was 8.9 g/m^2/d while at 125 to 250 mg N/dm^3, the yields increased from 22 to 45 g/m^2/d, at light intensity of 381 μE/m^2 second. The total amino acids content was 41 to 38 percent and crude protein was 55 to 50 percent in the Chlorella vulg. cell mass. The product yield and cell density decreased with retention time which varied from 2.5 to 6.7 day.

The aim of these studies was to find out the feasibility of algal treatment of biological effluent from Plant A, the cell yields and protein content of recovered biomass and to estimate design parameters for a full scale system.

Experimental Methods

The studies were conducted in a system of four ponds in series, with facilities for collecting intermediate samples. The ponds were placed in a photostat and lighted continuously (24 hr/day) by fluorescent bulbs. Temperature was approximately 23 ± 3°C which was equal to room temperature.

Two parallel series of four ponds each, were used, with volumes of the ponds: series A - 20.0, 21.45, 23.15 and 40.0 dm^3; series B - 19.6, 21.0, 22.95, and 40.0 dm^3; the overall surface areas were: F(A) = 4,669 cm^2 and F(B) = 4,707 cm^2. The corresponding retention times were: A = 3, 9, 18, and 21 days and B = 6, 12, 24, and 25 days in all four ponds.

The influent wastes were metered by peristalitic pumps. The wastes were collected from the final clarifiers at the Vidus type treatment Plant A. The wastewaters fed to the ponds had extremely variable quality which had a profound effect on the performance and made interpretation quite difficult. The values of $BOD_{5,f}$ varied 8 to 220 mg O_2/dm^3, COD_f = 9 to 1,038 mg O_2/dm^3, PV_f = 28 to 470 mg O_2/dm^3, $N\text{-}NH_3$ = 147 to 900 mg/dm^3, $N\text{-}NO_3$ = 1 to 153 mg/dm^3, $N\text{-}NO_2$ = 1 to 994 mg/dm^3.

The treatment efficiency of the ponds was determined on the basis of physical-chemical parameters: pH, BOD, COD, DO, SS, TKN, $N\text{-}NH_3$, $N\text{-}NO_2$, $N\text{-}NO_3$, PO_4, Total P, potassium; and on the basis of biological analyses and biomass harvesting yields, protein content and amino acids composition. Biological analysis included species definition, total cells counts and counting of dividing cells.

The system was seeded with a mixture of Chlorella vulg. and Scenedesmus pure algal cultures, the samples were collected after the passing of five retention times. Only one seeding was made, thus, the system was subject to cyclic (Harmonic in nature) variations in the biomass content.

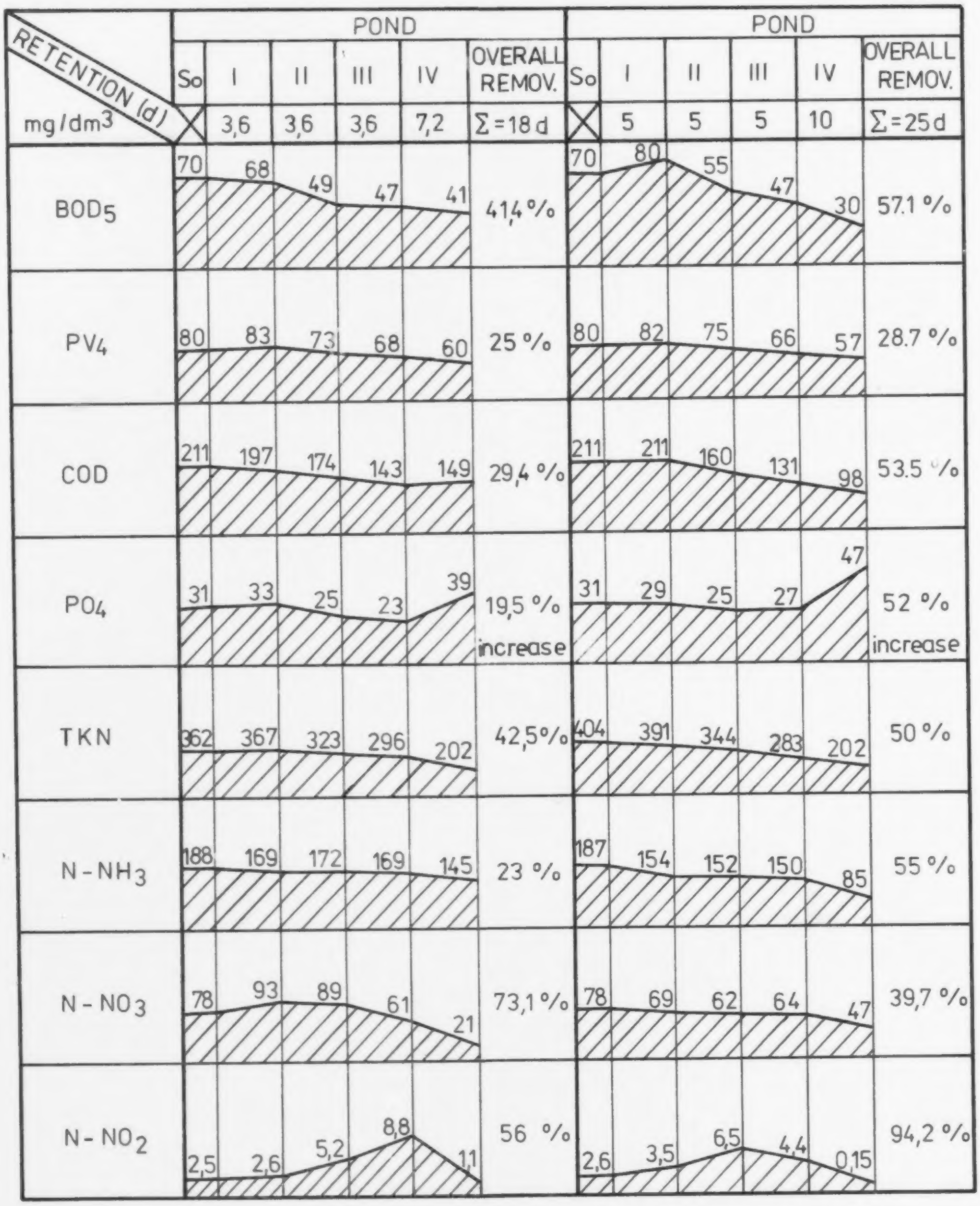
Results

Biological data could not be correlated with physical-chemical data. It is assumed that this was due to the contamination of the system with algae in final clarifier effluent as compared to original seeding culture, the temperature variations, algae are quick to react to minor environmental changes, extremely large influent concentration variability and the fact that 24 hr/day lighting was used. As noted by Matusiak et al. (103), the lighting plays a very significant role in the studies and intermittent lighting as used in their experiments had profound beneficial effects on the algal performance. The biological studies were also clouded because of the fact that experiments were run in flow through, continuous systems maintained for several months with one original seeding. As found by several other researchers (104) in such systems, the biomass quality and quantity, particularly in laboratory conditions exhibits oscillations with decreasing magnitude.

Since the detailed results contain close to 1,000 individual data points, only major findings will be summarized here. Typical performance of the ponds is depicted in Figure 23 for retention times of 18 and 25 days both during October and November, 1979. In all experiments phosphates content increased significantly, indicating decomposition of total phosphorus in the biological effluent and coming from the decay of algal cells. In three instances there was an increase of the content of $N\text{-}NO_3^-$ indicating completion of nitrification. The removals of ammonia nitrogen were from 20 to 65 percent. The values of BOD_5, COD and permanganate COD decreased steadily in all cases. In long hydraulic retention times (HRT) runs, the secondary decay of algae has introduced error in these considerations. The data is condensed in Table 7. Each efficiency is calculated as an average of the whole run, taking into account the HRT.

Data Interpretation

The removal efficiency and effluent quality from algal ponds is dependent inter alia on the HRT and surface area loading (AL). So far in the literature, there are very few instances where successful correlations or removal against AL and HRT were attained and data is usually reported in terms of average biomass yields and gross removal ranges without kinetic interpretation. The first attempts in this study have revealed the reason for such approach. At low influent waste concentration to the ponds, the removal rate coefficient was affected by the influent wastes concentration, which made the interpretation impossible without dividing the data into S_o concentration groupings.



RETENTION (d) / mg/dm3	POND So	POND I	POND II	POND III	POND IV	OVERALL REMOV.	POND So	POND I	POND II	POND III	POND IV	OVERALL REMOV.
		3,6	3,6	3,6	7,2	Σ=18 d		5	5	5	10	Σ=25 d
BOD_5	70	68	49	47	41	41,4 %	70	80	55	47	30	57.1 %
PV_4	80	83	73	68	60	25 %	80	82	75	66	57	28.7 %
COD	211	197	174	143	149	29,4 %	211	211	160	131	98	53.5 %
PO_4	31	33	25	23	39	19,5 % increase	31	29	25	27	47	52 % increase
TKN	362	367	323	296	202	42,5 %	404	391	344	283	202	50 %
$N-NH_3$	188	169	172	169	145	23 %	187	154	152	150	85	55 %
$N-NO_3$	78	93	89	61	21	73,1 %	78	69	62	64	47	39,7 %
$N-NO_2$	2,5	2,6	5,2	8,8	1,1	56 %	2,6	3,5	6,5	4,4	0,15	94,2 %

Figure 23. Averaged effects of treatment in a series of four ponds. An example for 18 and 25 days HRT runs.

TABLE 7. CHARACTERISTIC OVERALL REMOVAL EFFICIENCY ATTAINED IN THE SERIES OF FOUR ALGAL PONDS

Retention (days)	3	6	9		12				18		21	24	25	
Dates	Mar. 21 to April 6 1979	Mar. 21 to April 6 1979	May 3 to June 6 1979	June 19 to Aug. 10 1978	Feb. 5 to Feb. 24 1979	May 3 to June 8 1978	April 19 to Aug. 10 1978	Feb. 5 to April 24 1979	Sept. 7 to Oct. 12 1978	Oct. 20 to Nov. 17 1978	Dec. 8 to Jan. 16 1979	Nov. 29 to Jan. 16 1979	Sept. 7 to Oct. 5 1978	Oct. 12 to Dec. 17 1978
Removal (%)	1	2	3	4	5	6	7	8	9	10	11	12	13	14
$BOD_{5,f}$	11	5.5	62.8	51.5	34	74.8	65	50.5	65.5	41.4	27	19	53.8	57.1
COD_f	4	29.4	-	-	4	-	-	18.7	-	29.4	27.6	32	-	53.5
PV-cod	0	8.3	42.6	32.1	(+)	34.6	41	(+)	48.7	25	22.2	3.2	62	28.7
$N\text{-}NH_3$	-	-	22	4	-	19	0	-	32	23	42.6	41	56	55
$N\text{-}NO_3$	-	-	3	36	-	(+)	25	-	(+)	73	40	(+)	(+)	66
$N\text{-}NO_2$	-	-	(+)	48	-	(+)	53	-	65	55	75	96.6	96	31
$P\text{-}PO_4$	-	-	(+)	(+)	-	(+)	(+)	-	(+)	(+)	(+)	(+)	(+)	(+)
$S_o BOD_{5,f}$ mg O_2/dm^3	18	18	113	66	97	115	66	97	58	70	63	63	58	70
$S_e BOD_{5,f}$ mg O_2/dm^3	16	17	42	32	64	29	23	48	20	41	46	51	26	30
Load g $BOD_5/m^2/d$	1.35	0.65	2.88	1.60	2.41	2.11	1.22	1.77	0.74	0.88	0.67	0.56	0.52	0.71
S_o PV mg O_2/dm^3	24	24	258	109	52	240	112	52	115	80	63	63	115	80
S_e PV mg O_2/dm^3	24	22	148	74	63	157	66	56	59	60	49	61	44	57

(+) Increase of concentration in the effluent.

The effluent quality, expressed in permanganate COD (PVcod) showed a predictable increase with the increase of AL (g/m^2 d) (see Figure 24-B). The correlation for BOD_5 was not acceptable, while the same correlation for COD_f ($g\ O_2/dm^3$) yielded a straight line (55):

$$S_e(COD) = 0.0278.AL; \qquad (14)$$

up to 20 $g/m^2/d$; beyond that point it begun leveling off toward an asymptote parallel to AL axis.

Figure 24-A shows the correlation of removal efficiency against AL of $BOD_{5,f}$. It is characteristic that the efficiency increases with the influent substrate concentration.

The scatter of data points, symptomatic for majority of algal studies in flow-through systems, does not preclude a definite delineation of different curves. This is further evident in the kinetic interpretation in Figures 25 and 26. The first order removal plot usually assumed for pond systems:

$$(S_o - S_e)/HRT = k\ S_e \qquad (15)$$

in Figure 25 shows poor agreement even when data is pooled into four raw concentration groupings $S_o \leq 60$, $S_o = 61$ to 105 units, $S_o = 106$ to 150 units and $S_o > 150\ mg/dm^3 - BOD_{5,f}$. A much better removal is shown in Figure 26 where the authors have applied a novel kinetic model:

$$(S_o - S_e)/HRT = k\ (S_e/S_o) \qquad (16)$$

which incorporates the effects of influent substrate concentration. The model constant is named substrate kinetic removal constant and correlates the algal ponds removal data with satisfying accuracy. It is interesting to note that Hebrowska (104) has observed similar effects of concentration on the increase of removal efficiency.

In order to find an optimum retention time, plots of efficiency and biomass yield against HRT were made as shown in Figure 27. Plot A demonstrates that biomass yields are not well correlated against time and that the expected production based on laboratory data at 23°C, should be below 10 g $DM/m^2/d$ at retention times around 15 days. It follows from part B of the same figure that

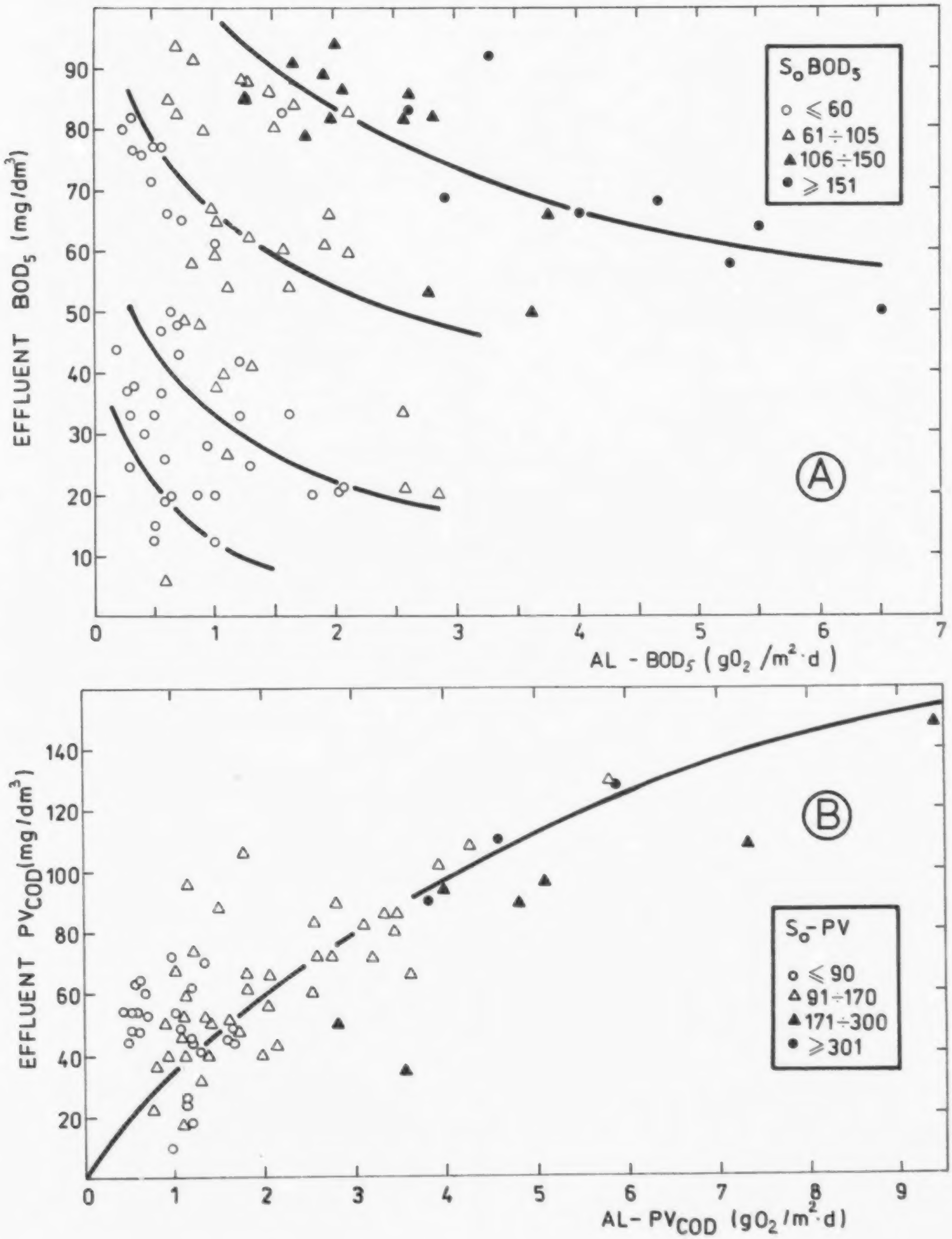


Figure 24. Efficiency of $BOD_{5,f}$ removal and permanganate COD in the effluent from four ponds system.

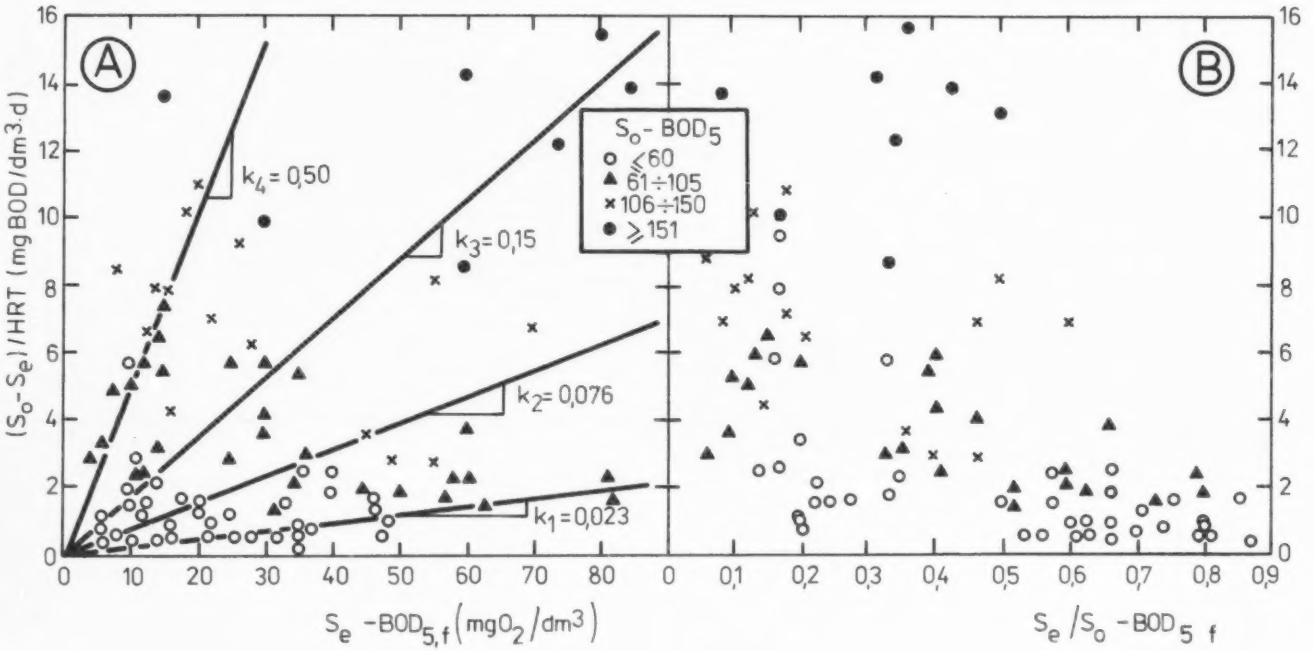


Figure 25. Kinetics of $BOD_{5,f}$ removal in series of four ponds: (A) First order; (B) Authors' model - substrate kinetics data pool.

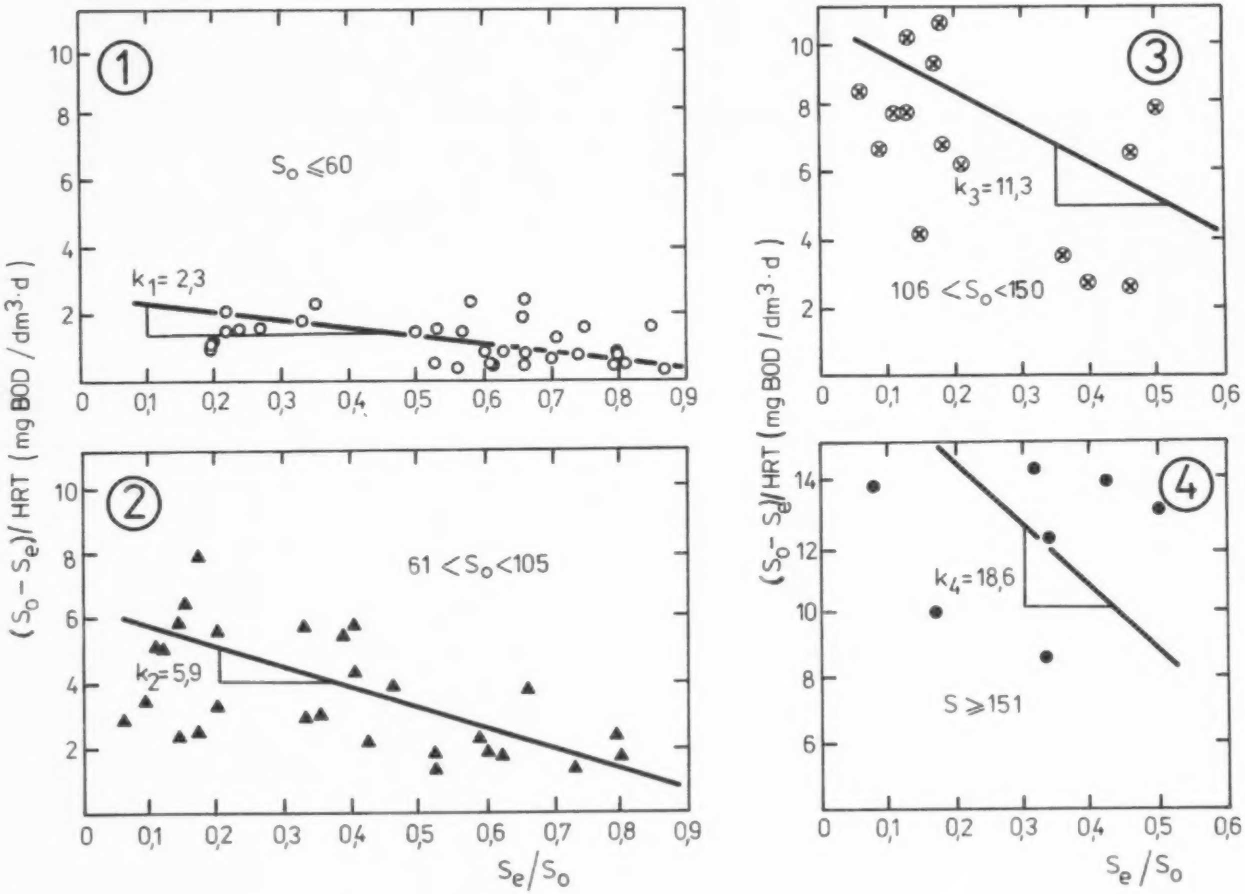


Figure 26. Kinetics of $BOD_{5,f}$ removal in algal ponds; four influent concentration ranges - authors' substrate model.

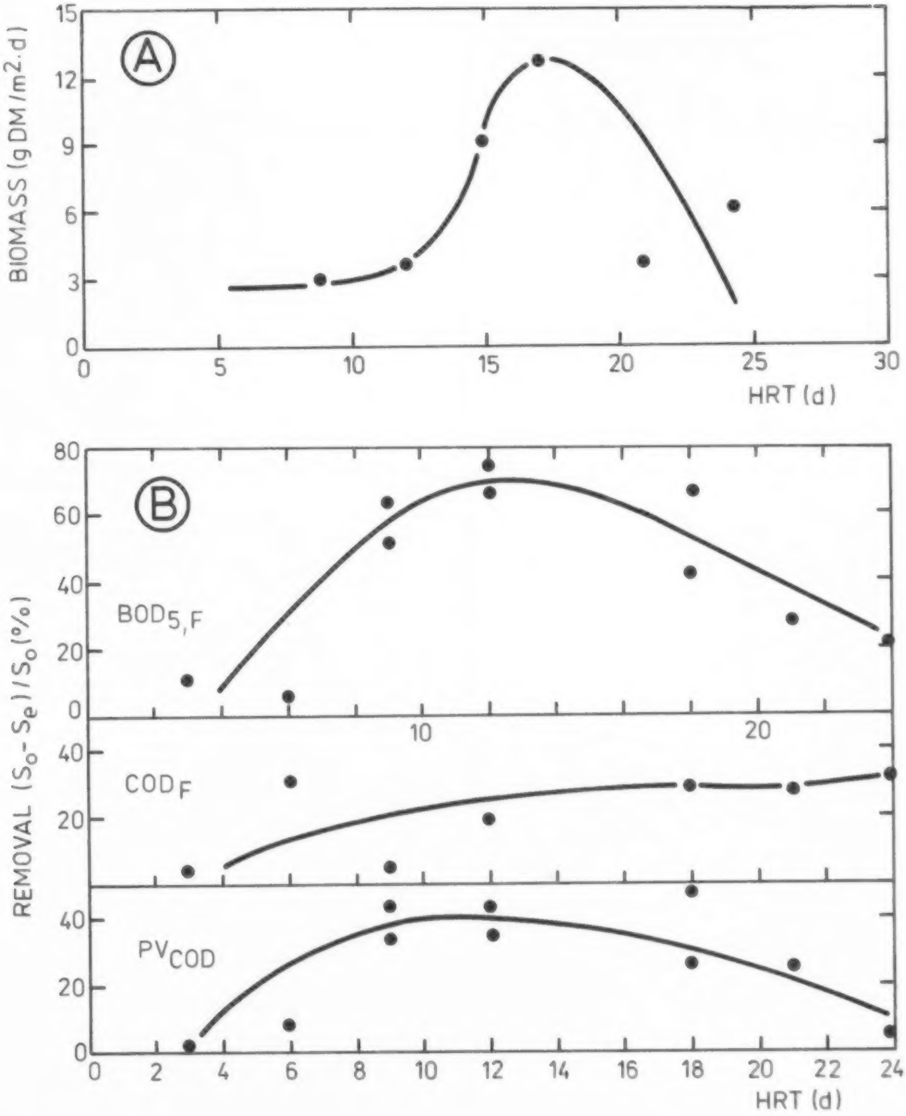


Figure 27. Efficiency of algal biomass production and optimum retention for organics removal in algal ponds.

the optimum retention time is 9 to 12 days, thus the expected algal biomass yield is 3 to 4 g DM/m^2/day.

In the studied case of Plant A the full scale ponds are presently constructed. The design criteria and expected yields are: HRT = 15 d, AL = 10 g $O_2/m^2/d$ - COD_f, removal efficiency - 50 percent for COD, BOD_5, biomass yield 2 g/m^2/day. Fish will be planted in the final pond, thus the biomass will not be harvested mechanically.

Conclusions

The system of four ponds was found very difficult to interpret due to several overlapping interactions and disturbances. The biological information, such as algal cells and bacterial cells counts could not be correlated with physical-chemical parameters. Decay of algae and resulting secondary containation of the system has resulted in significant distortions of the data.

It has been found that the removal efficiency is increased with the increasing substrate concentration. A new model (S_o-S_e/HRT = k(S_e/S_o) introduced by the author was found adequate for data interpretation, provided data was pooled into narrow raw wastes concentration ranges.

The expected efficiency of the algal ponds in summer conditions is over 50 percent removal of organics, at HRT = 10 days and with simultaneous biomass production of over 3 to 5 g DM/m^2/day. It should be borne in mind that the diurnal cycle of natural light will increase significantly the efficiency of the algal ponds beyond yields obtained with this study. Based on those assumptions, a full scale fish pond system is presently installed.

POLISHING ANAEROBIC BIOFILTRATION

Full scale waste treatment train at Plant A contained an anaerobic filter filled with sponge as the main polishing, mechanical filtration unit. Due to clogging, overflowing and solids carryover, the filters were put out of operation. The authors have reconstructed the filter, its inlet and the washing system and replaced the sponge media with coke on a gravel underlayer. The studies reported have been conducted between January 1 and June 1, 1979.

Detailed discussion of results obtained and the modifications on the two parallel biofilters at Plant A is presented elsewhere (21, 105, 106).

The wastewaters were fed to the biofilters from the final clarifier (Figure 5), and on the average had the following characteristics: $BOD_{5,f}$ = 30 mg/dm^3 (range 10 to 140), $BOD_{5,nf}$ = 70 mg/dm^3 (18 to 180), COD_f = 205 mg/dm^3 (range 44 to 480), COD_{nf} = 410 mg/dm^3 (100 to 1320), N-NH_3 = 110 mg NH_4/dm^3 (range 68 to 250); VSS = 78 (2 to 380), TDS = 1040 mg/dm^3 (540 to 2400). The characteristic removals attained were on the average 40 percent $BOD_{5,nf}$ (30 percent $BOD_{5,f}$) and 38 percent COD_{nf} (30 percent COD_f). Major problems encountered were due to significant influent concentration variability as noted in the range of numbers.

The kinetic of removal in the biofilters, interpreted by means of the author's model, details in Section 4, are presented in Figure 28. Two fairly distinct operations regimes are evident, the change of removal rate occuring at L = 1.0 to 1.5 kg/m^3/d. Otherwise, it should be stressed that the biofilters were exhibiting fairly stable removal characteristics, proportional to the load applied.

Discussions and Conclusions

The full scale anaerobic biofilters in the modified version with coke media offer short retention time and 30 to 40 percent removal of organics. The denitrification occurs to only a small degree, due to rather high organic loadings, high influent nitrogen concentrations. The removal of nitrites and nitrates varies from 20 to 44 percent. Due to incomplete nitrification, the total nitrogen content in the effluent is still excessively high. Ammonia nitrogen content in the effluent is 40 to 160 mg N/dm^3. The biofilters remove almost no ammonia nitrogen, at times an increase occurs which is indicative of incomplete aerobic biooxidation in the aeration tank.

The biofilters exhibit up to 20 percent increase in the effluent suspended solids, the concentrations being TSS = 60 to 270 mg/dm^3 and VSS = 20 to 80 mg/dm^3, which indicates high level of mineralization in the sloughed-off sludge.

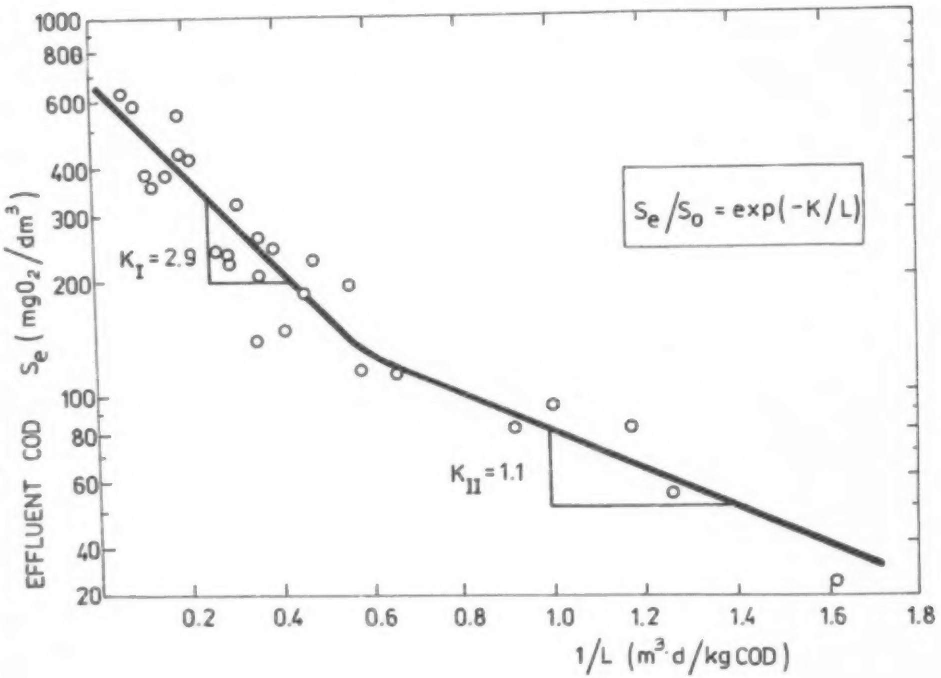


Figure 28. Removal kinetics in full scale anaerobic polishing biofilters.

It is concluded that the biofilter working in the operational regime, average values in parenthesis: L=0.3 to 2.8 (1.10) kg BOD/m^2/d; 0.2 to 1.6 (0.7) kg BOD/m^3/d, 1 to 13 (3.7) kg COD/m^3/d at hydraulic loading of 6.5 to 11.5 (9.4) m^3/m^3/d provides insufficient nitrogen removal. Insufficient breakdown of the organic matter in the preceding aerobic biotreatment yields further production of N-NH_3 in the anaerobic biofilter. Due to high organics loadings, the denitrification did not proceed to satisfactory levels.

SECTION 8

ANAEROBIC TREATMENT

INTRODUCTION

The anaerobic treatment has been traditionally applied for almost a century to sewage sludges, more as a method of sludge stabilization than energy recovery. Recent increases in animal wastes generation rate and the mounting energy crisis directed designers towards anaerobic digestion of wastewaters. The conventional flow-through anaerobic digestors have been regarded as applicable to wastewater with influent COD concentrations above 4000 mg O_2/dm^3 (13, 57). The other popular contention among the animal waste anaerobic treatment researches was that the lower limit of total solids qualifying wastewaters for anaerobic digestion was two percent. This stemmed from the fact that the small farm wastes had much higher concentrations of organics, that flow-through systems were used and no reliable data to the contrary was reported. Recent re-introduction of the contact or sludge recycle process to treatment of the more dilute effluents has shown that there are no lower concentration limits to efficient anaerobic digestions. The increasing interest was stimulated also by the fact that at higher concentrations, e.g. above 20 g/dm^3 COD, the aerobic treatment has been found to be four times as expensive as equivalent anaerobic treatment (89).

This work will demonstrate that the flow-through anaerobic digestion without sludge recycle is feasible on wastes with TS below one percent and COD_{nf} around 10 g O_2/dm^3. Several process modifications will be studied as presented in Figure 29. The batch studies will be conducted to obtain the adequate volume of seeding sludge. Following the batch tests, flow-through studies will be conducted at varying detention times to test the lower limit of the HRT and efficiency of methane generation from the unit of organics removed. In order to further cut down on the HRT, contact digestion studies

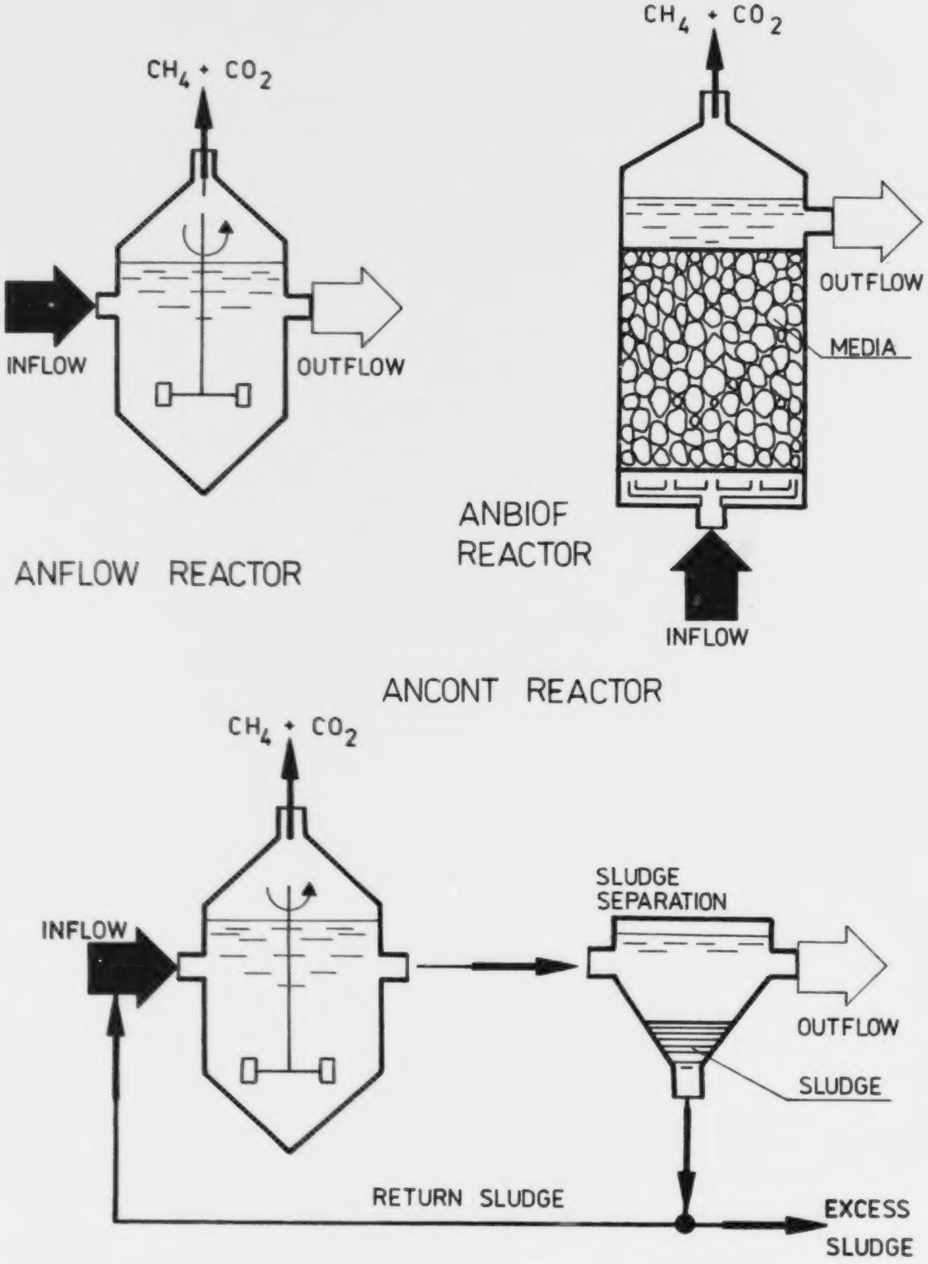

CH4 + CO2
INFLOW
OUTFLOW
ANFLOW REACTOR
CH4 + CO2
OUTFLOW
MEDIA
ANBIOF REACTOR
INFLOW
ANCONT REACTOR
CH4 + CO2
INFLOW
SLUDGE SEPARATION
OUTFLOW
SLUDGE
RETURN SLUDGE
EXCESS SLUDGE

Figure 29. Layout of various anaerobic treatment process modifications studied.

will be run in a continuously fed, gas mixed reactor with sludge recycle.

The main problems of the contact digestion system are the generation of dispersed anaerobic sludge that settled poorly, and thus makes the control of the sludge concentration MLSS in the reactor difficult. In order to alleviate this problem anaerobic biofilters will be tested as the modification of the contact process where sludge is attached to the filter media rather than being retained in the system through recycle (Figure 29).

Anaerobic treatment of piggery wastewaters in concentrated form has so far been confined to the batch or flow-through studies in laboratory scale (67, 69, 70) or pilot studies (71, 72). So far there have been no anaerobic studies on the treatment of dilute piggery wastes from large farms, and no contact digestion studies on any hog wastes reported so far. The experiments reported supply, then the parameters of the fermentation and methane generation kinetics of dilute piggery wastes and will provide basic process design data.

Practical Aspects of Anaerobic Biodegradation

Anaerobic wastewater treatment processes have not found wider use for several reasons:

1. Aerobic processes were considered more rapid.
2. Power costs expended for aeration were much less noticed before the onset of current energy shortage.
3. Anaerobic processes were thought unreliable and fit mostly for organic sludges.
4. Anaerobic pathways are still not agreed upon; the multitude of kinetic equations used in modelling the process is not easy to apply by the designers.
5. The optimum conditions and process operating parameters are not well known; the designers in all cases have to rely on feasibility studies.
6. There is generally established contention that anaerobic processes are much more easily susceptible to toxicity and other environmental stresses than aerobic processes, and that the recovery time is significantly longer.

Basically, during anaerobic fermentation, at least three intermediate steps can be distinguished (90): 1) liquefaction or hydrolyzation of complex polysaccharides (cellulose), proteins and lipids by fermentative bacteria to organic acids, alcohols, H_2 and CO_2; 2) acetogenesis by the group of H_2-producing, acetogenic bacteria, which obtain energy for growth by producing acetate CO_2, H_2 from acids and alcohols produced by liquefaction; and 3) methanogenesis, i.e. utilization of H_2, CO_2, and acetate in the production of final products, CH_4 and CO_2. Hashimoto et al. (96) have recently presented a mechanism with four groups: first, hydrolytic bacteria; second, hydrogen producing acetogenic bacteria; third, homoacetogenic bacteria forming acetate from H_2, CO_2, and formate; and fourth, the methanogenic bacteria. Detailed knowledge of the process is still lacking as noted by Balch et al. (97). Thus, for all practical purposes, a basically diphasic process is considered here, with acidic phase preceding the rate determining (i.e. slower) methanogenic phase.

In an actual fermenter the two processes are occurring simultaneously. The methanogenic bacteria being strict, fastidious anaerobics are reproducing slowly, and thus, the minimum design retention time is limited by the sludge age or SRT (biomass). There are three distinct optimum operational temperature ranges: 1) psychrophilic 5 to 15°C; b) mesophilic 30 to 35°C; and c) thermophilic 50 to 55°C. The increase of temperature is accompanied by the decrease of the minimum doubling time.

In view of the above, the decrease of the volume of the anaerobic reactor (cost minimization) may be obtained by means of increasing the temperature or sludge age, while keeping the HRT down.

With highly concentrated animal wastes, TS above 6 to 10 percent, the increase of reactor temperature should be considered. Since sludge age cannot be effectively increased due to solids separation problems, various researchers have optimized the volume of the flow-through-anaerobic-reactors without sludge recycle down to five days (HRT=SRT=5 d) at 55°C (91, 92, 93), i.e., operation within the thermophilic range.

With dilute effluents such as the piggery wastewaters described in Chapters 1 and 2, the best way of bringing the HRT down is to increase the SRT by solids recycle or retention as in the heterogeneous (fixed film) reactor.

BATCH DIGESTION

Batch digestion tests initiated all anaerobic experiments and were continued throughout the studies in order to provide seed and at the same time test possible inhibitory charges to the reactors.

Experimental Method

The studies were conducted in 3 dm^3 glass vessels, kept in thermostats at $35^{\circ}C \pm 0.5^{\circ}C$. The method has been adopted after Chmielowski (52). The setup is presented in Figure 30. The vessels were sealed with specially designed valves containing thick rubber membrane that allows multiple perforations by hypodermic needle of a syringe feeding the tank and evacuating accumulated biogas to the manometer. The biogas was vented once per day, the pressure was compensated by the Boyle-Mariotte equation, so data is reported in standard temperature and pressure conditions (STP). The error due to gas solubility in liquid phase is ± 1.5 percent. The changes of volume of the digesting liquor due to the introduction of substrate were taken into account in calculating the volume of biogas produced. After measuring the gas pressure, calculating volume, and feeding the substrate, the pressure was equalized with ambient pressure. Excess pressure during substrate feeding warranted air-tight operation.

Three series of experiments were conducted, each was initiated differently. In all experiments raw piggery wastes from Plant A were used after screening and sieving. The first series consisted of introducing actively digesting municipal sludge fermented in controlled laboratory conditions. Seven vessels were fed 1 dm^3 of sludge each, the air was evacuated by purging with propane-butane mixture. The vessels were placed in $35^{\circ}C$ and gas production (GP) was monitored daily. When GP definitely slowed, to each of the six vessels, 0.1 dm^3 aliquots of piggery wastes were added, the seventh was left unfed as a reference for calculating GP from the seed sludge alone.

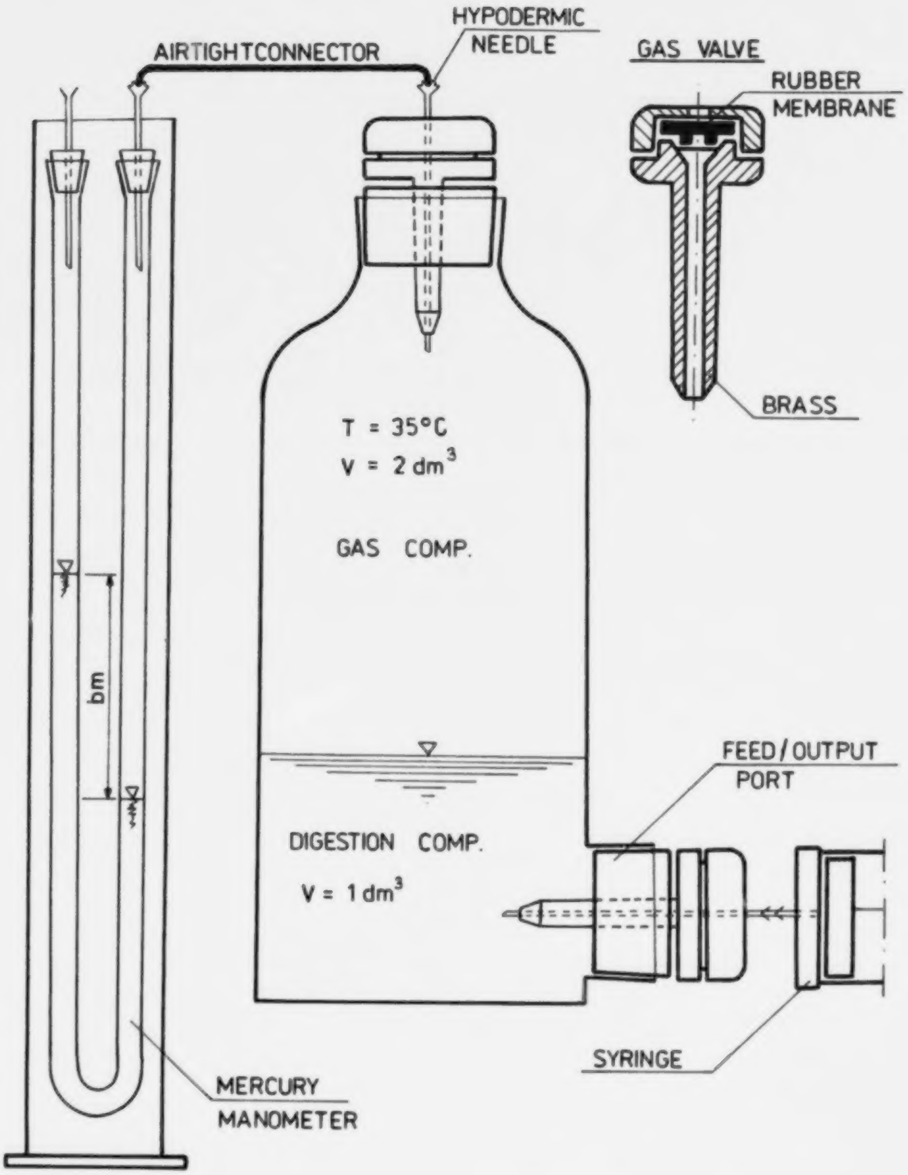

HYPODERMIC NEEDLE
AIRTIGHTCONNECTOR
GAS VALVE
RUBBER MEMBRANE
BRASS
T = 35°C
V = 2 dm^3
GAS COMP.
bm
FEED/OUTPUT PORT
DIGESTION COMP.
V = 1 dm^3
SYRINGE
MERCURY MANOMETER

Figure 30. Pressurized glass reactor used as batch and ANFLOW reactor.

The second series was initiated with pig wastes and sludge from the first series. Here 0.2 dm^3 of wastes were added to 1 dm^3 of seed mass in the vessel, the first feeding was at the start of experiments.

The third series was initiated with digested effluent from the second series, and conducted the same as the second one, 0.2 dm^3 of wastes were fed at the decrease of GP.

Results--

The full results of all three experiments are summarized elsewhere by Oleszkiewicz et al. (94) and Janiczek et al. (95). The quality of manure fed into the laboratory vessels varied as follows: pH = 7.1 to 7.7; $BOD_{5,nf}$ = 1,500 to 14,000 mg O_2/dm^3; COD_{nf} = 4,000 to 2,600 mg O_2/dm^3; total nitrogen = 600 to 1,700 mg N/dm^3; chlorides = 100 to 190 mg/dm^3; total alkalinity = 30 to 70 milivals/dm^3; TS = 2,200 to 15,000 mg/dm^3; TVS = 1,700 to 9,200 mg/dm^3; TDS = 300 to 4,500 mg/dm^3; VSS = 150 to 3,300 mg/dm^3; TSS = 1,600 to 11,000 mg/dm^3; VSS = 850 to 6,700 mg/dm^3.

The overall gas production from the introduced organic matter to six vessels in Series III is presented in Table 8, while Table 9 presents the arithmetic averaged specific gas production data from all three series, all data is based on nonfiltered samples. The GP_o denotes volume of biogas generated from the load introduced.

TABLE 8. BIOGAS PRODUCTION IN SERIES III

Tank	1	2	3	4	5	6
SERIES I	TOTAL LOAD INTRODUCED ΣL_o DURING EXPERIMENT TVS = 3.29 g, BOD = 3.6 g, COD = 8.19 g					
ΣGP (cm^3)	1428	670	2196	956	1673	685
SERIES II	ΣL_o: TVS = 2.848 g, BOD = 2.35 g, COD = 6.12 g					
ΣGP (cm^3)	2383	2002	2060	2283	2484	2020
SERIES III	ΣL_o: TVS = 6.016 g, BOD = 8.46 g, COD = 18.88 g					
ΣGP (cm^3)	6369	7618	5713	7274	6685	No Data

TABLE 9. SPECIFIC GAS PRODUCTION FROM INTRODUCED ORGANIC LOAD - BATCH STUDY

	SGP_o - Biogas Production Per Unit of Introduced Load (m^3/kg):		
Series	TVS	BOD	COD
I	0.383	0.450	0.154
II	0.775	0.940	0.361
III	1.120	0.796	0.356

The results indicate that only periodic acclimation of digesting biomass to introduced wastewaters will produce satisfactory results in a short period of time. In these experiments the initial seed to manure proportions were 8:1 to 10:1, and the minimum start-up time was 80 to 90 days. The gas production data (SGP_o) indicates that daily variations of wastewater concentration do not influence directly the daily gas production (GP_o - cm^3/d) whose fluctuations as seen in Figure 31 cannot be explained at this stage of experiments.

The increasing SGP_o from Series I to Series III indicates both the positive influence of degree of acclimation and effects of increased concentration of organics in the input.

Conclusions

The batch digestion tests have proved the feasibility of anaerobic fermentation of dilute screened piggery wastes. Over 80 percent degradation of organics was achieved. The SGP_o attained from the introduced organic load varied with the increasing degree of acclimation of the fermenting biomass and reached 0.36 m^3/kg COD, 0.9 m^3/kg BOD and 0.8 to 1.1 m^3/kg TVS.

CONTINUOUS STUDIES IN ANFLOW REACTORS

A majority of the screening and treatability tests on anaerobic digestion are run in batch or semi-continuous reactors, mixed once or twice per day. Various researchers have found that such intermittent random shaking provides completely mixed conditions from the standpoint of the process kinetics (52).

After testing the effects of intermittent mixing and the effect of the length of acclimation to new environmental conditions on process efficiency

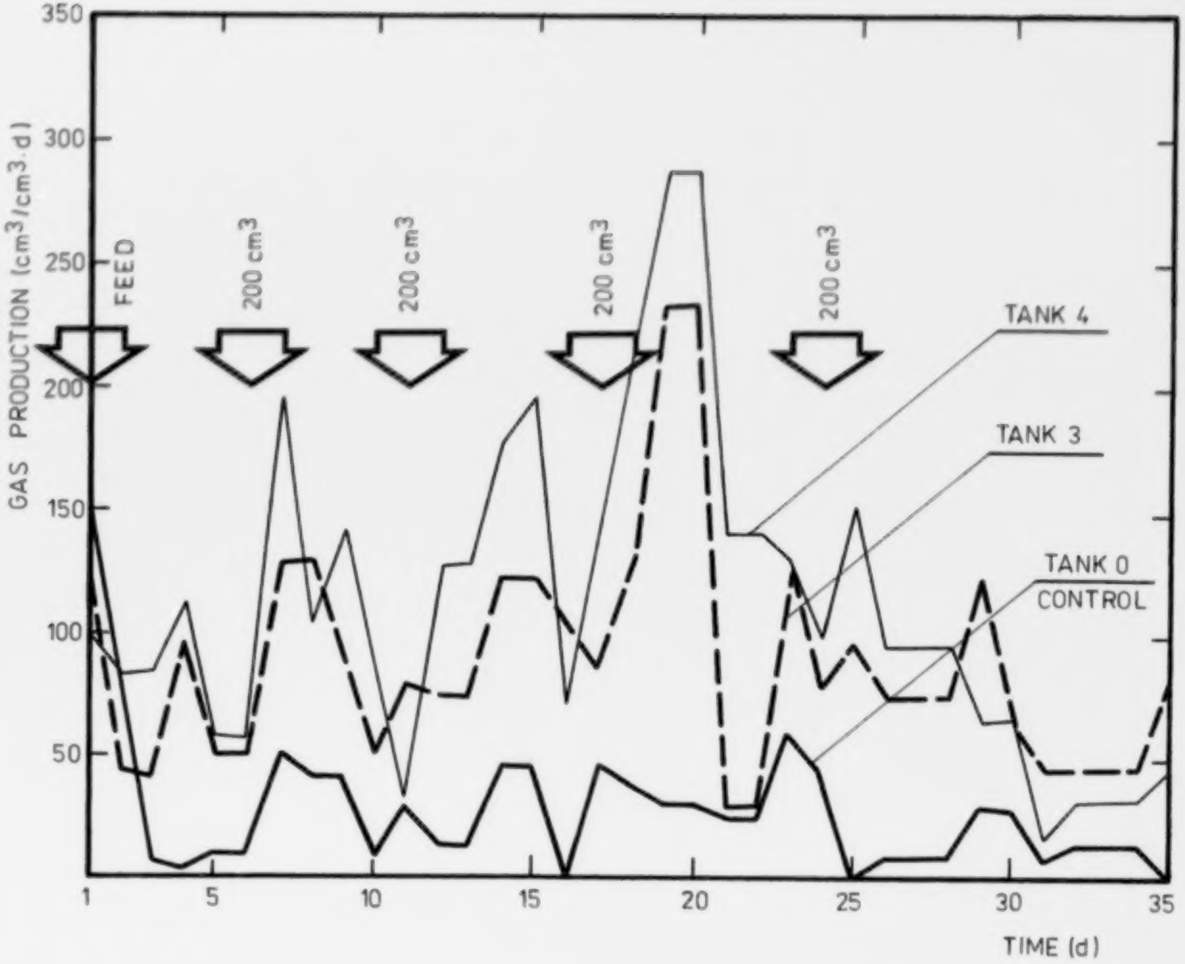


Figure 31. The course of batch anaerobic digestion in the third series of experiments.

as discussed above, the continuous tests were initiated in completely mixed, flow-through reactors without recycle called the ANFLOW reactors.

Experimental

The raw piggery wastewaters were collected in separate containers throughout one day and then mixed to arrive at the desired concentration. It was assumed that a relatively constant input COD concentration of approximately 2.5×10^3 to 14.5×10^3 mg O_2/dm^3 should be maintained through-out the experiment. The raw wastes were then sieved in order to facilitate unobstructed addition by a hypodermic syringe through the rubber membrane valve shown in Figure 30. The wastes were stored at 4°C for a maximum of one week.

The active volume digesting liquid was 1 dm^3. Raw piggery wastes were added once a day after the withdrawal of appropriate volume and determination of gas pressure and quantity. The fermenters were manually shaken at least two times a day to provide mixing. The volume of the output and input was determined on the basis of desired retention times. Seventeen retention times were tested: 1.5, 1.75, 2, 3, 4, 5, 6, 6.7, 8, 9, 10, 12.5, 15, 20, 25, and 30 days.

Six parallel fermentors were incubated at $33^\circ \pm 0.5^\circ C$ for each experimental period. The series at one retention time consisted of five individual runs, each run was sampled at steady state conditions, a total of $17 \times 5 = 85$ runs were made.

The analyses performed on samples from each run included: COD_{nf}, $BOD_{5,nf}$, TOC, SOC, TSS, VSS, SS, TS, pH, alkalinity, acidity, nitrogen compounds and random chlorides in raw and effluent concentrations were measured. A total of 190 analyses series were performed. Additionally, 17 gas analyses were made including CO_2, CH_4, N_2 and water vapor. One complete gas analysis was made for one retention time. Thus, the following data analysis is based on a total of over 2000 individual data points.

Definition of terms--

Since the available literature on anaerobic digestion is full of ambiguous notations of gas production, the following delineates unit GP parameters as

TABLE 10. RESULTS OF ANFLOW REACTOR PERFORMANCE

Retention Time in Days HRT	Concentration														
	pH	CH_4 (%)	COD_{nf} mg/dm^3		$BOD_{5,nf}$ mg/dm^3		TOC mg/dm^3		DOC mg/dm^3		TVS mg/dm^3		VSS	TSS	VSS_{end}
			S_o	S_e	S_o	S_e	S_o	S_e	S_o	S_e	S_o	S_e	-tank X_v	-tank X	-tank X_{ve}
1.5	6.3	25	14,370	11,530	5730	3990	4300	4180	1500	1220	5200	4780	2510	3760	1630
1.75	6.4	26.1	14,370	11,330	5730	3960	4500	4028	1500	1170	5199	4664	2506	3870	1590
2	6.5	28	12,870	10,320	5160	3550	3900	3350	1260	1130	4631	4045	2274	3470	1025
3	6.6	30.6	12,870	10,080	5160	3370	3900	3150	1200	900	4650	3520	2400	3495	1480
4	6.8	34.6	12,370	8,410	5160	2800	3900	2800	1200	540	4600	3100	2500	3700	1080
5	6.9	38	12,670	8,190	5160	2720	3900	2910	1200	1030	4800	3013	2500	3820	1355
6	7.2	47	12,720	7,400	5090	2640	3650	2320	1150	470	4310	2730	2410	3490	1410
6.7	7.3	50.1	12,370	7,620	5010	2390	3450	1530	1075	300	4520	2132	2410	3610	910
8	7.6	52.5	12,070	6,810	5160	2110	3900	1570	1200	250	4630	1865	2710	4030	1670
9	7.7	52.7	12,730	6,290	5090	1970	3650	1570	1150	260	4310	2130	2210	3430	1450
10	7.7	56.5	12,370	6,360	5010	2090	3430	1470	1075	230	4500	2330	2630	3050	1460
12.5	7.8	58.2	12,730	6,170	5090	1870	3650	1980	1150	240	4310	2530	1970	2910	1340
15	7.9	56.8	12,670	5,300	5010	1500	3450	1770	1075	250	4370	2590	1840	2140	1170
17.5	7.9	60.6	12,720	5,320	5090	1690	3650	1730	1150	200	4310	2720	2130	3140	1230
20	8.0	62.5	12,370	4,230	5010	1220	3450	2030	1000	220	4503	2620	1950	3010	1330
25	8.0	68.6	12,730	3,480	5090	860	3650	2080	1150	200	4310	2770	1930	2530	1310
30	8.2	65.8	12,570	2,640	5010	610	3450	2270	1075	210	4500	2600	1780	2710	910

*Each number is an arithmetic average of the whole run where several determinations were made.

An attempt was made to evaluate the viable or active cell content in the digestor. Substrate addition was halted and digestion was continued until there was no more gas produced. Then it was assumed that the VSS left were equivalent to the active biomass X_a. The ratio of the initial VSS - X_v to X_a varied fairly narrowly and as the average equalled 0.55, the value used was found as:

$$X_a = X_v \cdot 0.55 \qquad (22)$$

Results

Table 10 lists major analytically obtained parameters, without showing the calculated values of specific gas production and removals.

The analysis of the correlations between COD, BOD, TOC, SOC, and TVS showed that, based on Figures 32 and 33, there is a nonbiodegradable COD_{nf} of approximately 1200 mg O_2/dm^3, and that organic carbon data is not reliable as a straight line should have been obtained (Figure 32). Analysis of TVS biodegradability in Figure 33 shows that only TVS (1-R) = BVS = 0.49 TVS are biodegradable, and that there is a limit to $COD_{n,f}$ removal of some 80 percent.

The course of anaerobic degradation in the ANFLOW without recycle is depicted in Figure 34. It follows that the rate of effluent nonfiltered COD concentration decrease changes or slows down at t = 6 to 8 days at which point the content of the VSS is at a maximum mode at 8 days. The content of methane, which is an indicator of the degree of conversion of carbonaceous compounds, increases much faster than in data reported by Andrews (59).

The GP_{avg} has a maximum at 440 cm^3/day. This is equivalent to a production of 0.44 m^3/m^3/d at STP since the digesting volume was 1 dm^3 = 0.001 m^3 (see Figure 35). The maximum occurred at t = 8 d and then GP_{avg} started to decrease rapidly, while its calorific value, expressed as methane content increased steadily from 25 percent at 1.5 days through 53 percent at 8 days and to a maximum of 68 percent at a detention of 30 days. Other workers have noted higher CH_4 contents and in Figure 35, it is shown that the conversion of COD into methane continues beyond HRT = 30 days.

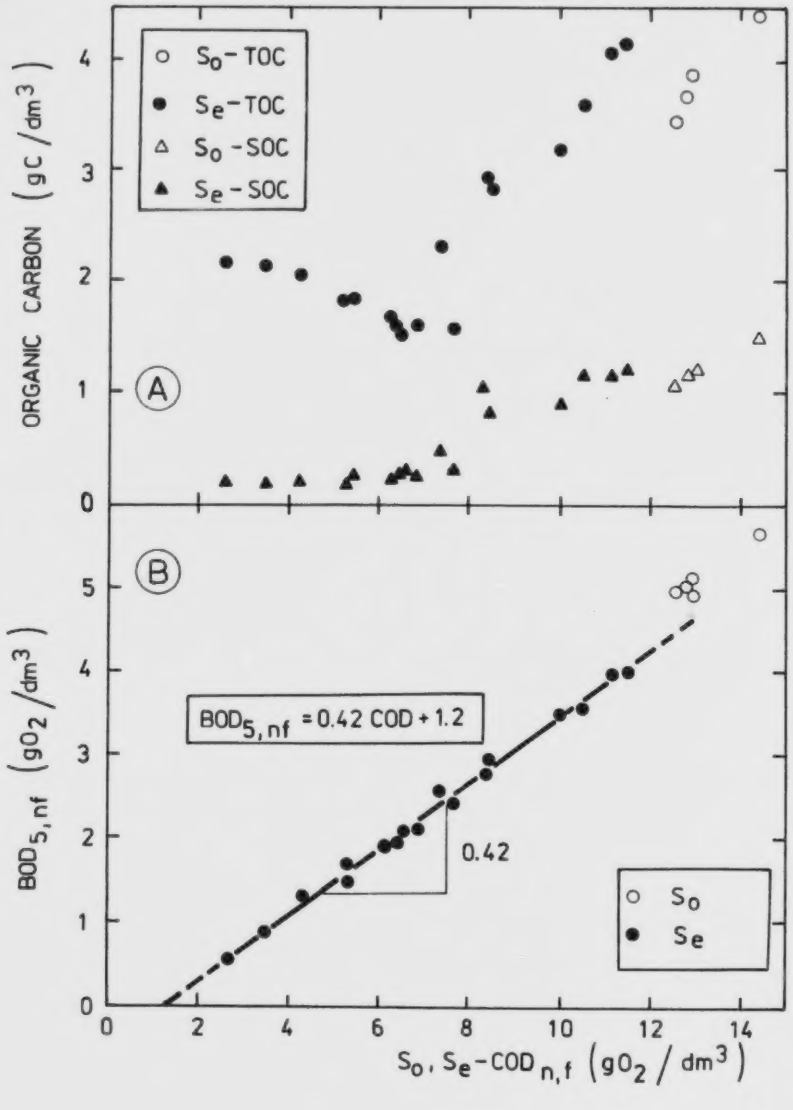


Figure 32. Carbon and BOD content, versus COD.

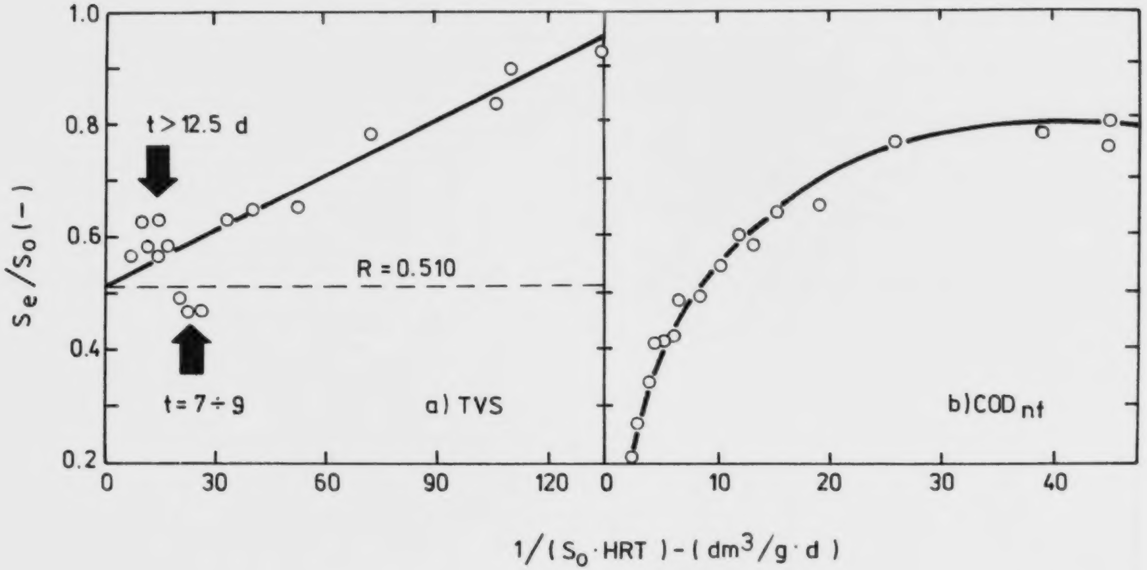


Figure 33. Anaerobic biodegradability of screened piggery wastes: (A) Based on total volatile solids; (B) Based on COD_{nf}.

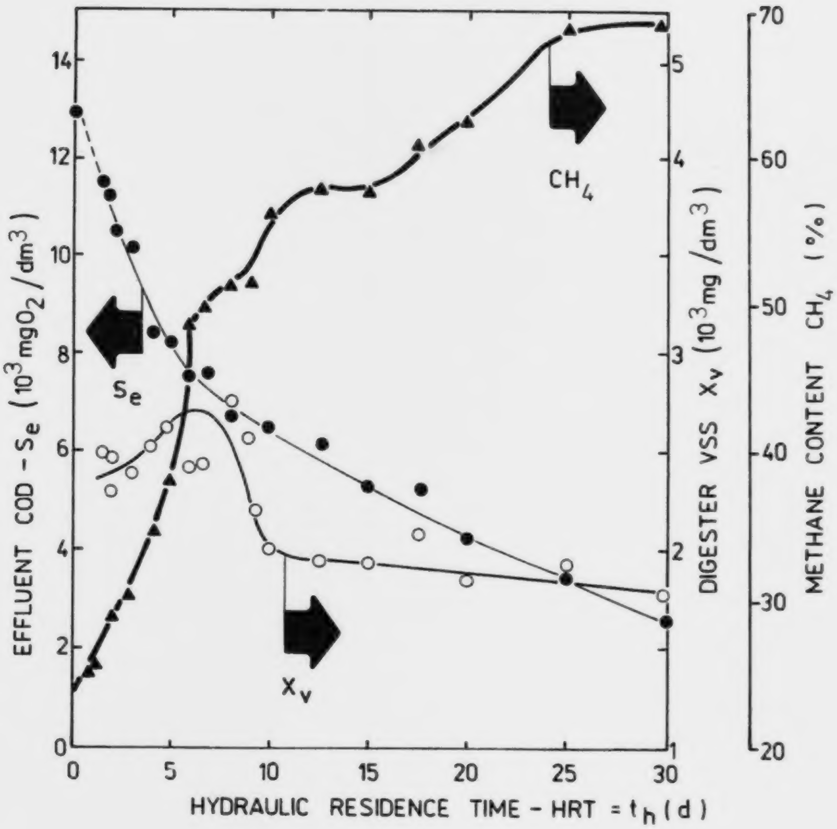


Figure 34. VSS content and removal of COD in ANFLOW reactor.

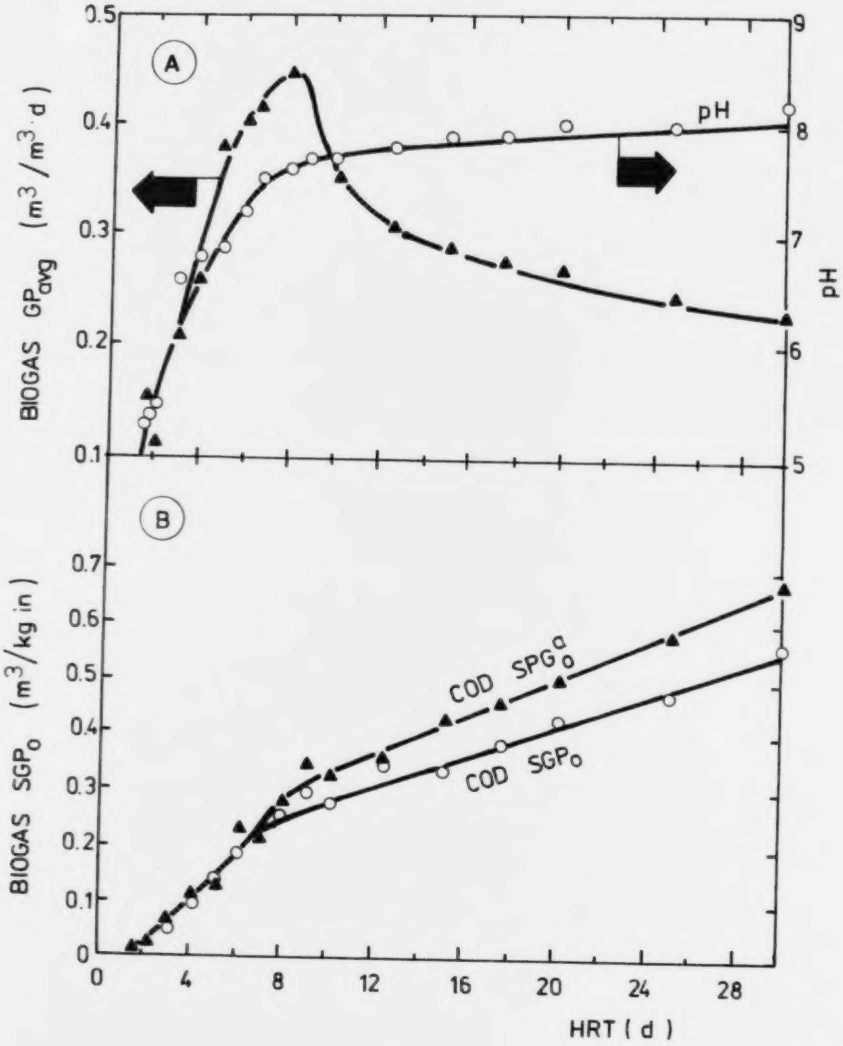


Figure 35. Gas production in ANFLOW reactor: (A) Overall average; (B) Specific gas production based on COD input.

Figure 36 illustrates the average methane production in m^3/m^3/day (B) at STP, from the ANFLOW reactors; and, the specific biogas production based on the introduced load of BVS.

The decrease in SGP_o^a - BVS at HRT = 8 days is interpreted as the completion of the liquefaction of organics. This is further documented in the A portion of the same figure which shows the decrease of the BVS concentration with time and proves that at 8 days, there is an abrupt change in the rate of BVS decrease, coincidental with change in the rate of pH changes (Figure 35) and indicative of start of a more balanced system of acidifiers and methanogens.

The data on biogas production from the removed load of organics should yield an aymptote close to theoretical carbon - methane conversion. Figure 37 shows that after HRT = 8 days, the rate of biogas production, Part A, is considerably slower, however, only in the SGP_r based on COD evidences a plateau like stretch. In the B portion of the same figure, at and beyond 8 days, the conventionally accepted maximum of SGP_r (CH_4) is reached, i.e., 0.334 m^3 CH_4/kg COD removed at STP, however, at 15 days the curve has a tendency to increase again. Literature perusal shows that other researchers have reported data for SGP_r (CH_4) up to 0.64 m^3/kg. The error cannot be excluded from our studies, however, since the four data points for HRT, 17.5 to 30 days, are from very small samples collected over a period of time.

Comparing gas production from the unit load of BVS, it appears that the SGP_o values are higher than obtained elsewhere, and there is a tendency to increase beyond 30 days (see Figure 38), which is not observed at data interpreted from the overall gas produced per overall load input (Figure 38-B) - SGP_o^a.

The technical design parameters may be obtained from Figure 39 where the decreasing COD load below 6 kg O_2/m^3/d yields continuous increase in the treatment efficiency. From the detention time, considerations (Figure 34) and from the analysis of gas production rates (Figures 35 and 36) at HRT = 8 to 10 days, there is a definite change in process efficiency. At these HRT values, the COD load is equivalent to 1.6 to 1.3 kg COD_{nf}/m^3/d and the expected

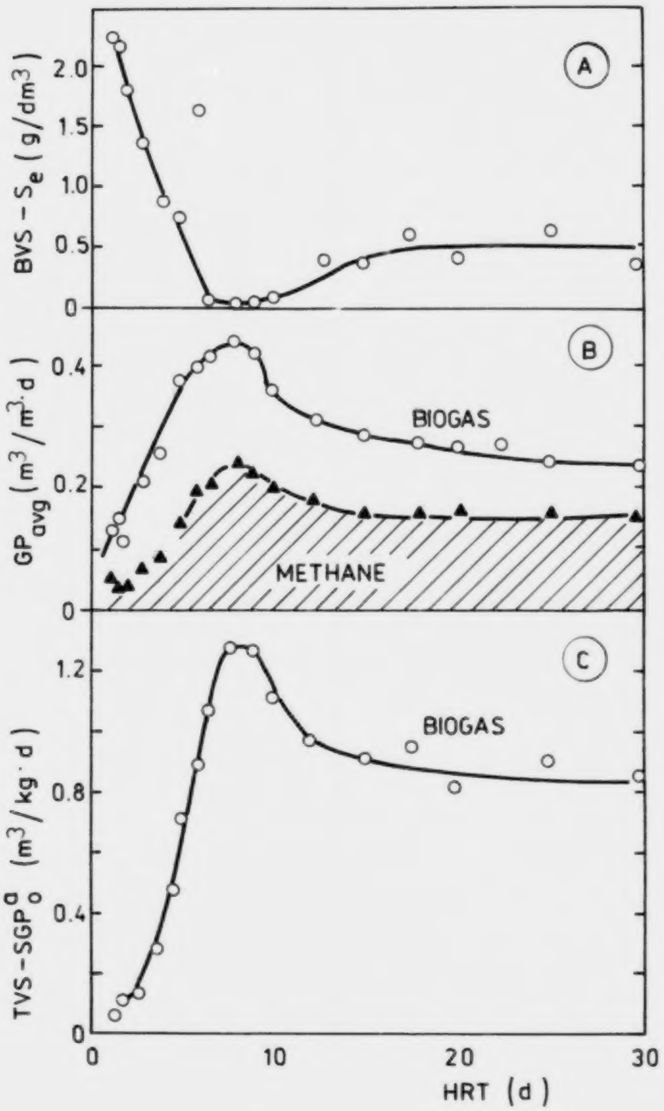


Figure 36. Kinetics of the ANFLOW reactor: (A) Removal of biodegradable VS; (B) Gas production; (C) Gas production from TVS introduced (SGP_o^a).

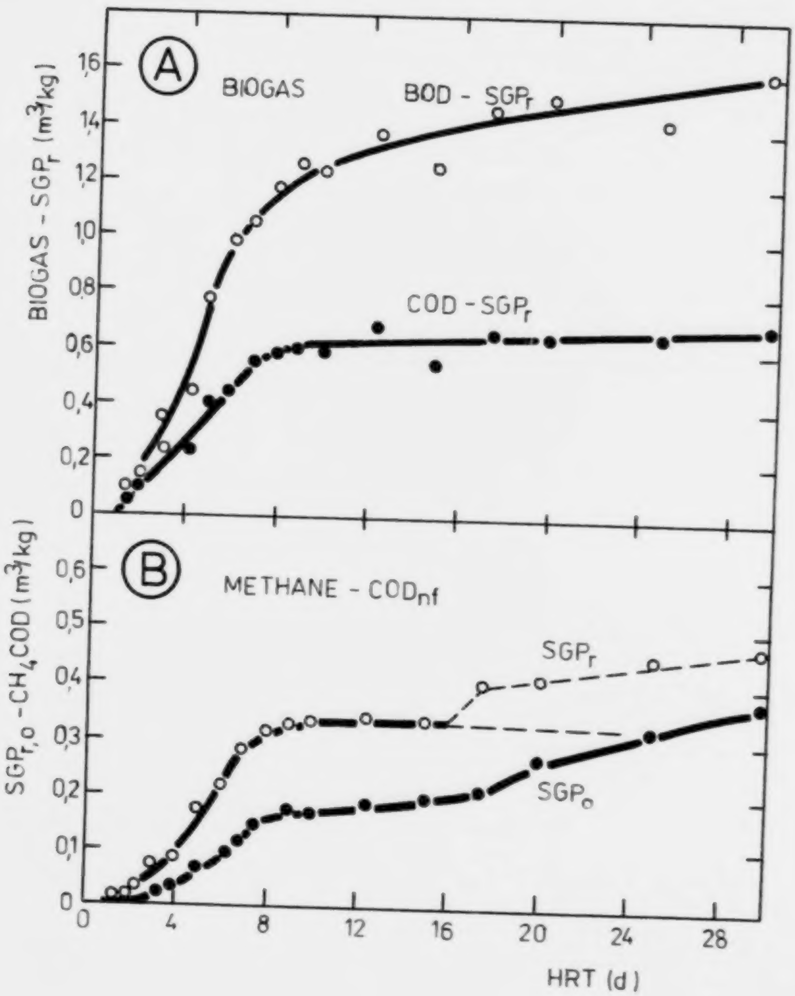


Figure 37. Gas production from removed $BOD_{5,nf}$ i COD - ANFLOW (Based on daily loadings).

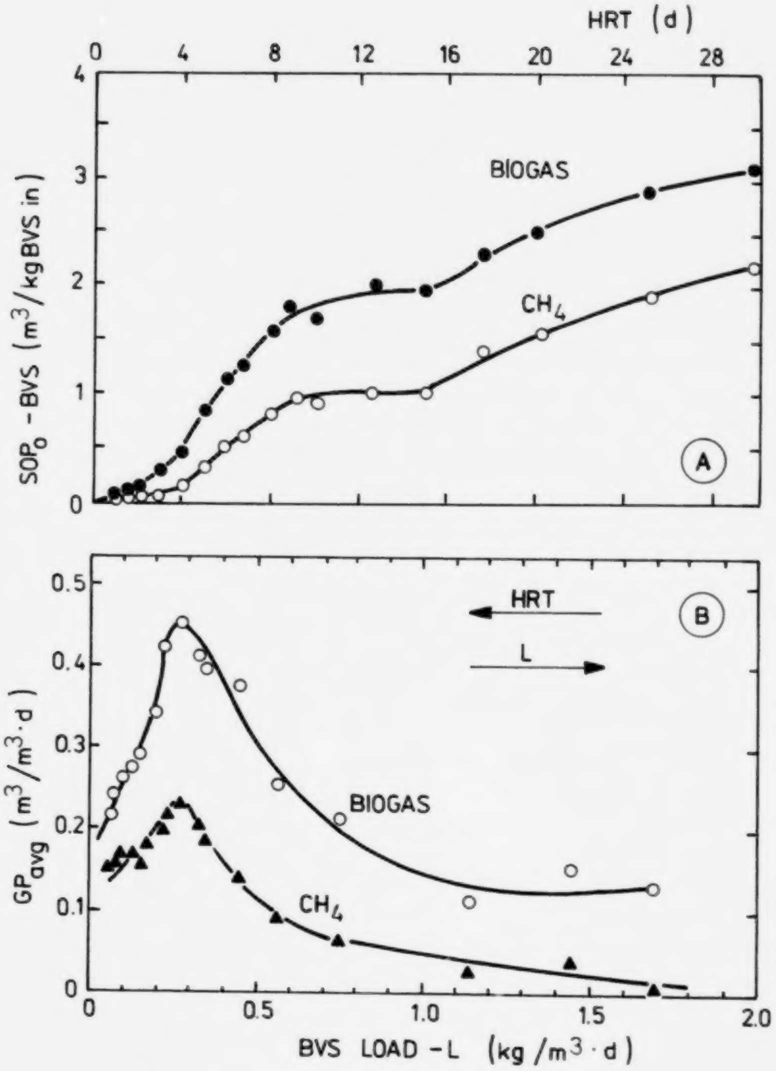


Figure 38. Gas production from biodegradable VS (BVS): (A) Based on daily loads; (B) Volumetric.

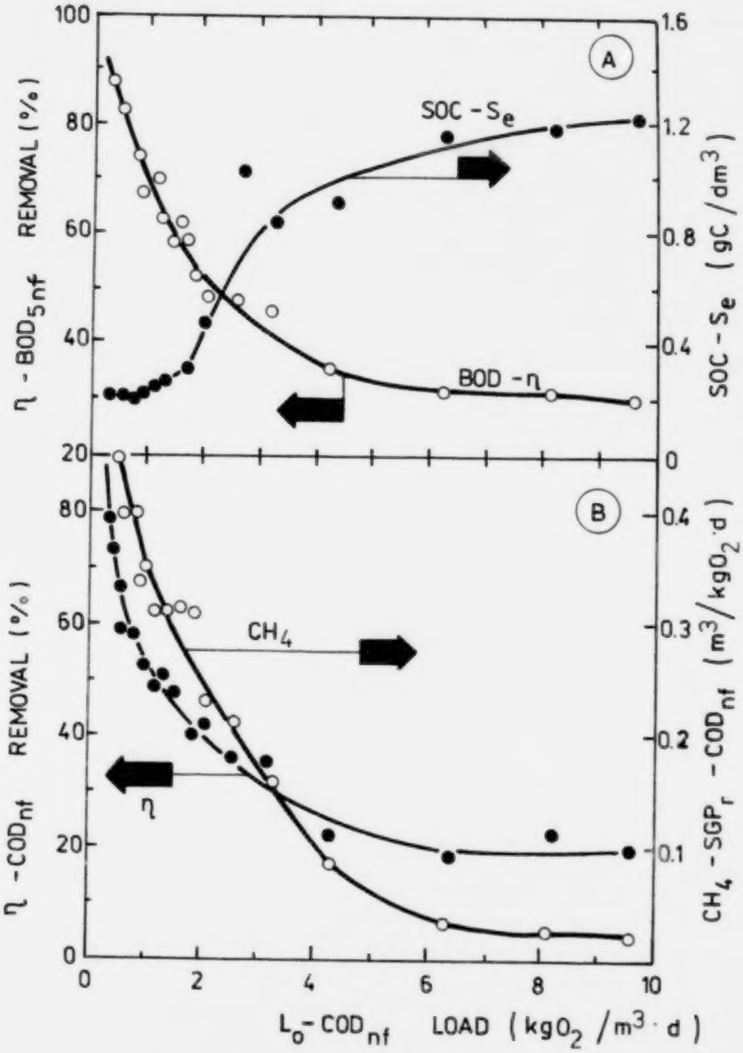


Figure 39. COD, BOD and SOC removal efficiency versus COD load in ANFLOW; unit CH_4 production from COD_r.

removals will be approximately: 50 percent COD_{nf}, 50 percent TVS, 60 percent $BOD_{5,nf}$, 58 percent TOC and 78 percent SOC; at the influent concentrations (mean from 85 data points): COD_o = 12,917 mg O_2/dm^3, TVS = 4,566 mg/dm^3, $BOD_{5,nf}$ = 5,164 mg O_2/dm^3, TOC = 3,764 mg C/dm^3 and SOC = 1,184 mg C/dm^3.

The removals cited above for HRT = 8 to 10 days refer to the BOD_5 loading of 0.65 kg O_2/m^3/d and TVS load of 0.6 kg/m^3/d or BVS of 0.3 kg/m^3/day. Since the wastes in this study are screened and sieved, thus considerable differences are noted when comparing this with other data. It is seen in Figure 40 where COD versus TVS concentration yields a relationship:

$$COD = M \cdot TVS = 2.66\ TVS \qquad (23)$$

while e.g., Morris et al. (80) have found for cow manure M = 1.43 g COD/g TVS.

Kinetics of growth and kinetics of removal--

Various interpretation methods are used, all empirical in nature. A simple and effective one has been suggested by Morris, Jewell and Loehr (80) as illustrated in Figure 40. The model is a hyperbolic relationship between time and fraction remaining of TVS. After transformation, it is R as the nonbiodegradable fraction = 0.51 g TVS/g TVS:

$$(TVS)\quad S_e/S_o = R + 1/\ k \cdot HRT \qquad (24)$$

and the plot yields k = 0.89 d^{-1} for this study, which compares well with 0.85 d^{-1} obtained by Morris et al. although the correlation is not satisfying.

Subjecting the data to the reaction order test, as used by Levenspiel (63), it is evident that the anaerobic degradation cannot be described by the zero or first order reactions with the active biomass (Figure 41-A). The value used for the active biomass concentration $X_a = 0.55\ X_v$ where 0.55 is the average ratio of VSS_e at the end to the initial VSS_o solids at the start of batch digestion without substrate addition which completed each series at a given HRT. Average values of the dimensionless ratio is used rather than individual values which ranged from 0.45 to 0.65.

Figure 41-B shows first order kinetic, simplified from Michaelis kinetics for $K_n >> S_e$ where the fit yields a reasonably straight line with slope

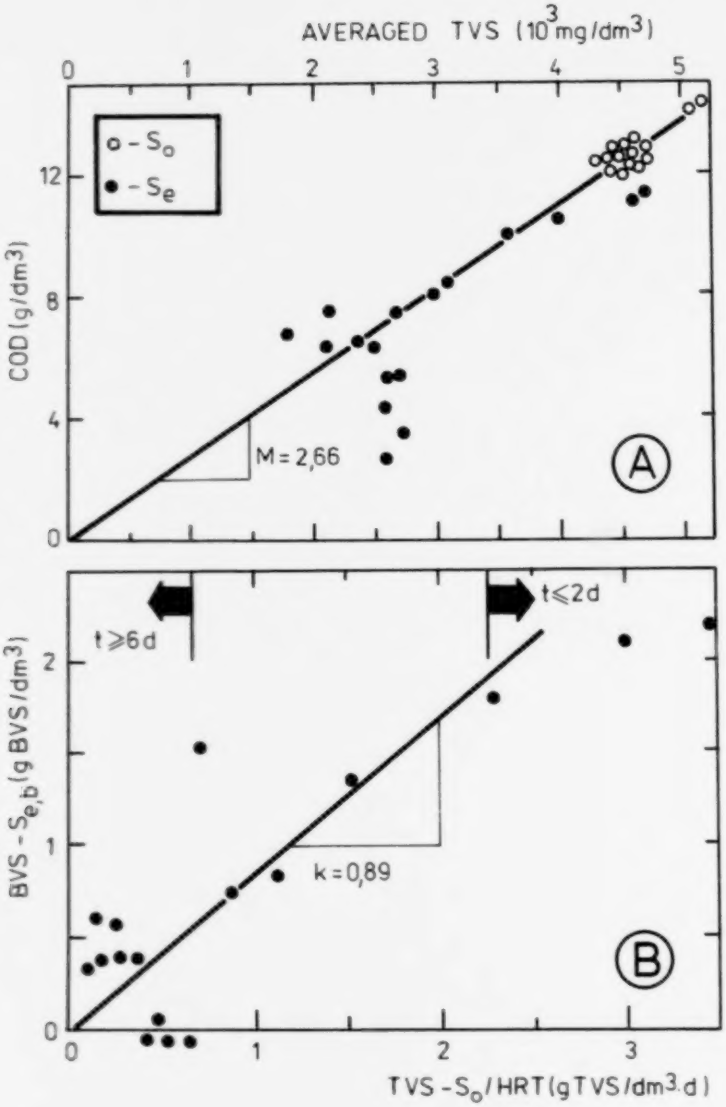


Figure 40. (A) COD dependence on TVS; (B) Morris, Jewell, Loehr kinetics of BVS removal.

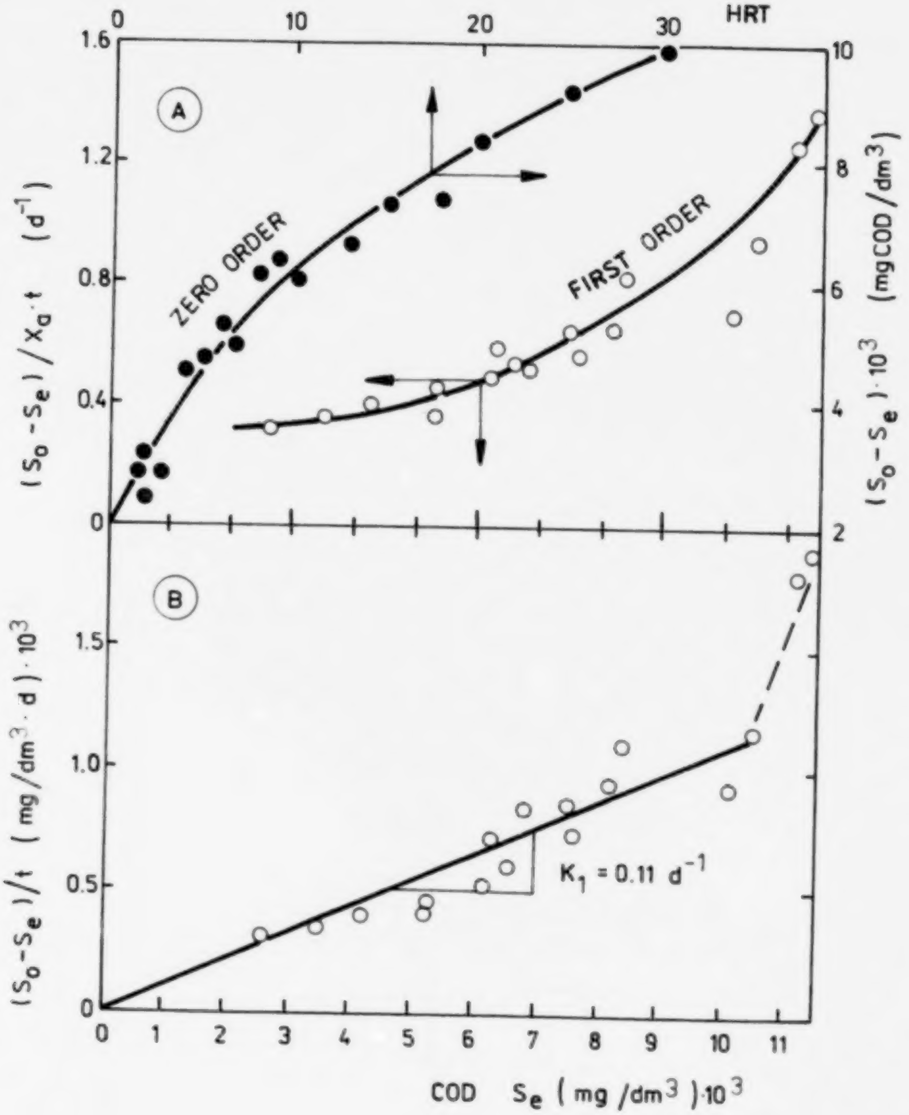


Figure 41. Zero and first order correlations of COD removal kinetics: (A) With active biomass (o) and zero order plot (•); (B) Without biomass.

$K_1 = 0.11\ d^{-1}$. Gaddy et al. (86) have shown, for cattle waste, $K_1 = 0.125\ d^{-1}$ from a similar plot.

Figure 42-A presents the growth correlations based on the $BOD_{5,nf}$ data from screened wastes according to a standard model, a transformation of the mass balance equation:

$$X_a = \frac{YS_r}{1 + bt} \qquad (25)$$

or

$$S_r/X_a = 1/Y + /b/Y/t \qquad (26)$$

where t = HRT. This method of interpretation proposed by Eckenfelder and Ford (58) yield a two-phase curve, the change of acidic into methanogenic phase occurring at HRT = 8 days and the coefficients equal to Y(a) = 1 mg VSS produced per mg BOD_5 removed; Y(n) = 0.59 (mg VSS/mg BOD_5); b(a) = 0.16 mg VSS used for endogeneous respiration per mg VSS in the reactor per day; b(m) = $0.11\ d^{-1}$.

Plotting the model of growth in the form:

$$1/t = \mu - b = qY - b = (S_r/X_a t)Y - b \qquad (27)$$

which is identical to the one above, one obtains a straight line as in Figure 42-B from which the yield coefficient Y = 1 and b = $0.11\ d^{-1}$ as for the methanogen phase in the A portion of the graph. This excessively large value of Y and b, the values found in literature do not exceed Y = 0.35, b = $0.05\ d^{-1}$ for anaerobic treatment is most likely the result of errors introduced by the TVS determination, noted by several researchers (87) and difficulties in determining the exact amount of biodegradable-active fraction of the biomass.

The applicability of the second order mechanism of growth (Monod empirical model) and removal (the Michaelis - Briggs - Haldane - MBH model) has been tested. Both proved inadequate, yielding, as in Figure 43-A, the MBH model, a curve rather than a straight line. Finally, the first order correlation was tried (Figure 43-B):

$$(S_e - S_{nb}) / (S_e - S_{nb}) = \exp(-kt) \qquad (28)$$

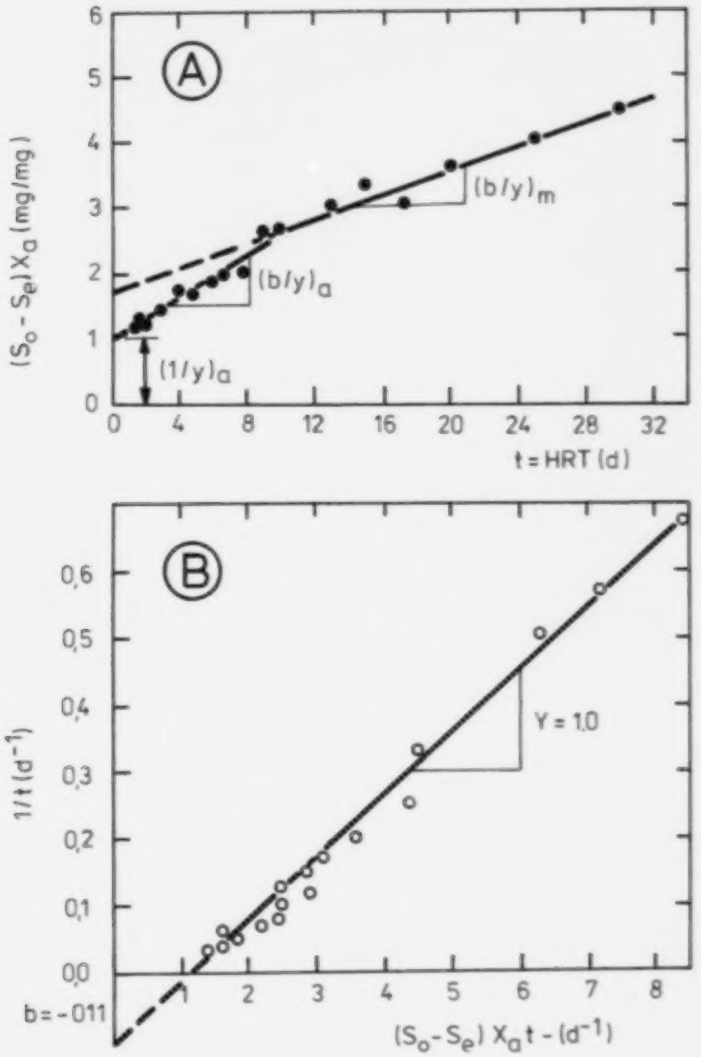


Figure 42. Growth kinetics correlation by two methods of interpretation - BOD$_5$ removal - ANFLOW reactor: (A) Eckenfelder and Ford; (B) This study.

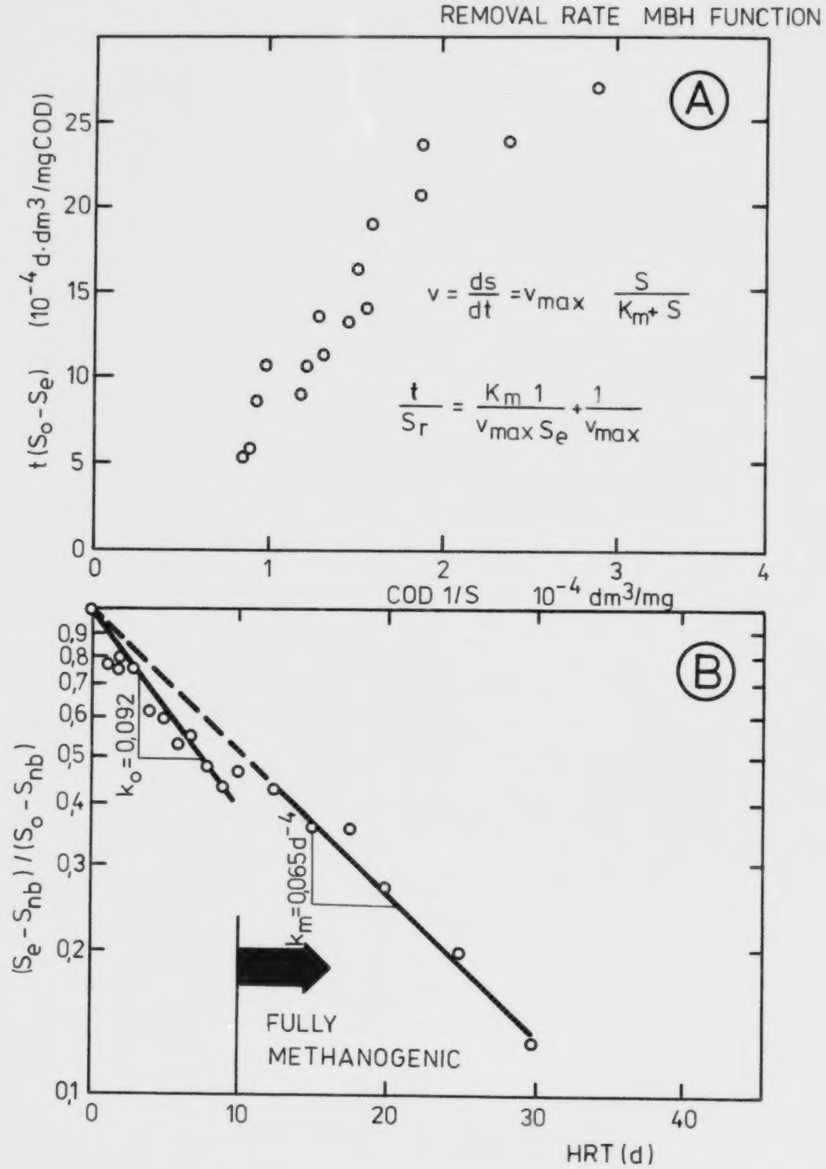


Figure 43. Removal kinetics in ANFLOW reactor: (A) Michaelis (MBH) second order; (B) Phase breakdown first order.

which is a plug flow approximation of a series of CMR. The rate coefficient $k_m = 0.065\ d^{-1}$ is adequately representing the data for HRT $\geq$ 10 d. The value of non-biodegradable COD was earlier estimated at 1200 mg O_2/dm^3. It is interesting to note that for poultry wastes Yang (82) has obtained $k = 0.09\ d^{-1}$.

Two distinct process kinetic constants are seen from Figure 43, i.e., for the acidic phase with $k_a = 0.092\ d^{-1}$ and the one suggesting a fully developed balanced methanogenesis $k_m = 0.065\ d^{-1}$.

Finally, plotting the data in the pseudo-first order plot of biodegradable fraction remaining of COD versus total COD load (L^{-1}), function one obtains two distinct data pools. For retention time HRT > 8 days, the load removal rate coefficient $k_m = 0.158\ kg/m^3/d$ as shown in Figure 44.

Discussion and Conclusions

Anaerobic digestion of piggery effluent in conventional ANFLOW reactors without recycle has received much attention. The data published is, however, full of ambiguous figures on gas yields and efficiencies; there also is a lack of concrete evidence as to the minimum critical TS concentration that can be effectively digested. Fischer et al. (67) have worked with a 35°C digestor with separate removal of sludge and liquid, thus, it was a semi-contact system in reality. They have found stable operation at 2.3 to 2.8 kg TVS/m^3 with gas production of 0.45 m^3/kg TVS removed (time unit not specified by authors). Extremely scattered data for those concentrated wastes contrasts with data from this project as well as the gas production, which at 15 days, amounted to 1.4 m^3/kg TVS removed (see Figure 35-A). Similarly Morris et al. (68) cites Loehr's data for swine wastes as $SGP_o = 0.434\ m^3$/kg TVS introduced. Our data shows gas production to reach a steady state level at SGP_o^a = 0.85 m^3/kg TVS introduced (Figure 36-C) Kroeker et al. (69) in his studies of ANFLOW with swine wastes loadings of 2 to 1 kg TVS/m^3/d obtained SGP_o = 0.68 to 0.82 m^3/kg TVS intr. and SGP_e = 1.98 to 1.62 m^3/kg TVS destroyed at SRT = 15 and 30 days.

The range of gas production reported in some references is depicted in Table 11. Larger H_4 production values than 0.334 $m^3/kg\ COD_{removed}$ reported as

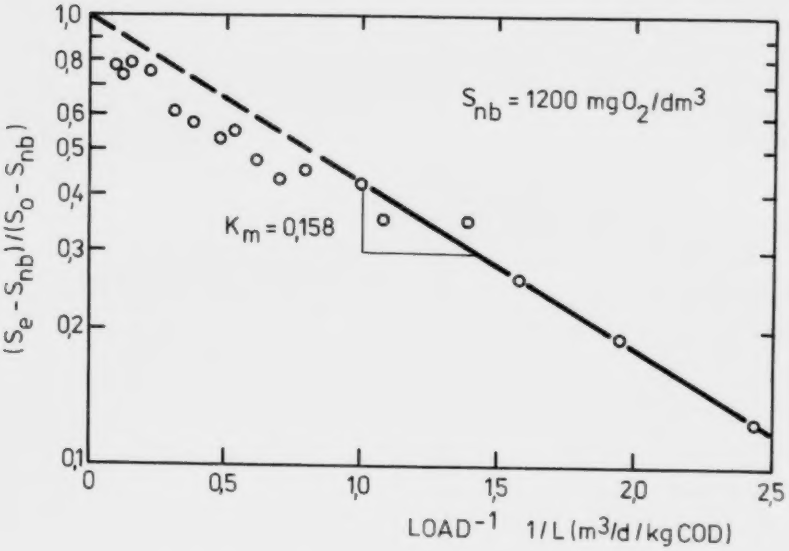


Figure 44. Pseudo-first order correlation of COD load versus remaining fraction of biodegradable COD.

TABLE 11. COMPARISON OF SPECIFIC GAS PRODUCTION SGP RATES AS QUOTED BY DIFFERENT SOURCES

Type of Wastes (Author):	Gas	SGP	Units m^3/kg of	Notes	Reference Number
"Theoretical" maximum	M	0.334	COD_r		61
Poultry manure	M	0.66	TVS_r	3 - 7% TS	75
Poultry manure	M	0.7 (m)	TVS_o		74
Poultry manure	B	0.93	TVS_o		74
MPS various sources	B	0.5-1.8	TVS_r		85
Fruit slops	B	0.47	COD_r		72
Molasses wastes	B	0.50	COD_r		72
Dairy cow	M	0.77	TVS_r	60%	84
Dairy cow	M	0.68-1	TVS_r	3 - 7% TS	75
Industr. sanit. sludge	M	0.3-0.64	COD_r		73
Various fruit-veget. wastes	M	0.2-0.42	TVS_o	HRT=32d, 0.7-1.6 kg TVS/m^3/d	155
SWINE WASTE					
Fischer, et al.	B	0.6-1.8	TVS_r	L=2.4-3 TVS	67
Fischer, et al.	M	0.77	TVS_r	Calcul.: 65% M	67
Solly	B	0.4-0.6	COD_o	Calcul.	77
Longsdom	B	0.6	COD_o	Calcul.	79
Overcash, et al.	M	0.31	COD_o	Calcul.	76
Sparling	B	0.5-1	TVS_r	57 - 60% M	78
Pipyn, et al.	M	0.3-0.65	COD_r	2-5% TS, t=10-30d	73
Kroeker, et al.	B	0.68-0.82	TVS_o	SRT = 15.30d	69

(Continued)

Table 11 Cont.

Type of Wastes (Author):	Gas	SGP	Units m^3/kg of	Notes	Reference Number
Kroeker, et al.	B	1.62	TVS_r	L=1.5 kg TVS/m^3/d	69
Summers, et al.	B	0.30	TS_o	6% TS raw	70
Morris, et al.	B	0.434	TVS_o		68
Ifeadi, et al.	B	0.5-1.3	COD_o	Calcul.	83
MPS guide	B	0.75	TVS_r	20°C, 12.5 d	85
Scharer, et al.	M	(0.62-0.94)	TVS_o	Value in m^3/m^3/d	153
Thomas, et al.	M	0.54	TVS_o	HRT 8.5 d; 79% M L=1.25 kg TVS/m^3/d	154
Thomas, et al.	M	0.25	TVS_o	HRT 2.6 d; 66% M L=5.6 kg TVS/m^3/d	154
Knol, et al.	M	0.33	TVS_o	HRT 32 d; 74% M L=1 kg TVS/m^3/d	155
Ngian, et al.	M	0.26	TVS_o	Batch, 38°C	156
THIS STUDY	M	0.334	COD_r	L=1 kg COD/m^3/d	
ANFLOW	B	0.88	TVS_o	L=0.5 kg TVS/m^3/d	
HRT = 9 d	B	0.60	COD_r		
L=1.4 kg COD/ m^3/d	B	1.2	$BOD_{5,r}$	L=0.6 kg BOD/m^3/d	
	B	0.3	COD_o	SGP^a_o = 0.35 m^3/kg	
	M	0.76	TVS_r	SGP^a_r	
	B	0.45	-	value in m^3/m^3/d	

m - minimum value is quoted

B - Biogas

M - Methane

Subscripts "r" - removed or destroyed; "o" - introduced "Calcul." denotes the use of 400 g COD/hog/d; at 100 kg live weight. Temperature is 35°C in all cases, except when specified.

maximum by McCarty et al. have been reported by Pypin and Verstraete (73) who attained 0.3 to 0.65 m^3 CH_4/kg $COD_{removed}$ for pig wastes.

It follows from the analysis of this data that gas production, although a reliable control parameter, should be carefully evaluated and procedures leading to the values quoted should be outlined.

The conclusions from this work may be itemized:

1. Flow-through digestion in ANFLOW without sludge recycle is feasible at very low concentration of TVS (0.5 percent) and COD (1.2 g/dm^3); thus, the lower limit for optimized digestion set by various researches as 2 percent TS is proven to be invalid.
2. Minimum required time for methanogenic digestion to develop is 8 days HRT.
3. Liquefaction is virtually completed at HRT = 8 days.
4. Maximum methane production is not coincidental with optimum retention for removal (i.e., 8 days), thus, sludge recycle is mandatory if one is to increase the reseeding and decrease the washout of methanogens and get lower values of HRT.
5. The method of seeding the digesters with acclimated digesting municipal sludge was applied successfully but long acclimation periods were necessary, over four months.
6. Lack of kinetic data evidenced in literature is the result of inadequate data base and perhaps also the inapplicability of the second order (hyperbolic) Monod or MBH kinetic models.
7. Piggery wastes are found to be easily biodegradable, with optimized conditions for biogas production and removal occuring at HRT $\geq$ 8 days.
8. The volatile suspended solids (MLVSS) content increases to a certain level and assumes steady state at t $\geq$ 10 days at VSS = 1750 mg/dm^3.
9. The parameter of TVS is inadequate due to analytical errors inherent in the standard test, the 600°C combustion includes some nonbiodegradables.

10. The results indicate the need for reliable re-evaluation of the theoretical and practical approach to gas production and for the establishment of criteria for evaluation of anaerobic digestion process performance.

11. Errors in evaluating SGP_o based on daily readings may be due to erratic daily GP; periods of low or inhibited gas generation lasted for more than 24 to 36 hours and were followed by intensive production; an average value then represented a better estimate, this was despite of mixing the ANFLOW contents.

ANAEROBIC DIGESTION IN ANCONT REACTORS

The anaerobic digestion studies in the ANFLOW reactor have shown feasibility at the hydraulic retention time, HRT $\geq$ 8 to 10 days. The decrease in the volume of the digestor can be made only through retention of sludge in the sludge recycle system similar to an activated sludge system. The ANCONT reactor designed in the project serves the purpose of complete mixing and sludge recycle, and was used to study the possibility of decreasing the HRT below 8 days.

Methods

Four parallel ANCONT reactors were used in the study. Each reactor, shown in Figure 45, was fed screened (15) raw pig wastes by a separate peristaltic pump (11) from tank (14) mixed through recycle (13) through conduit (12) and the feed pipe (6). The raw substrate enters the recycled sludge conduit and through injector (8) and recycle pipe (9) enters the central cylindrical completely mixed part of the reactor (2). After the contact with fresh sludge, the wastes enter concentric clarifier (3) and leaves the strictly anaerobic reactor through siphon (7) and (17). The siphon serves the purpose of level control and water seal. The treated wastes were collected in tank (16) and analyzed daily. The whole ANCONT (1) is made of plexiglass and placed in water bath (4), the temperature was controlled by thermoregulator (22), through electric heaters (21) with contact thermometers in the bath (2) and in the reactor (19). Gas was collected in a gas tank (5) with water seal (28) (NaCl brine in 15 percent H_2SO_4). The gas tank is equipped with counterweight (27), manometer (26), thermometer (25), and gas valves (23) for collecting gas

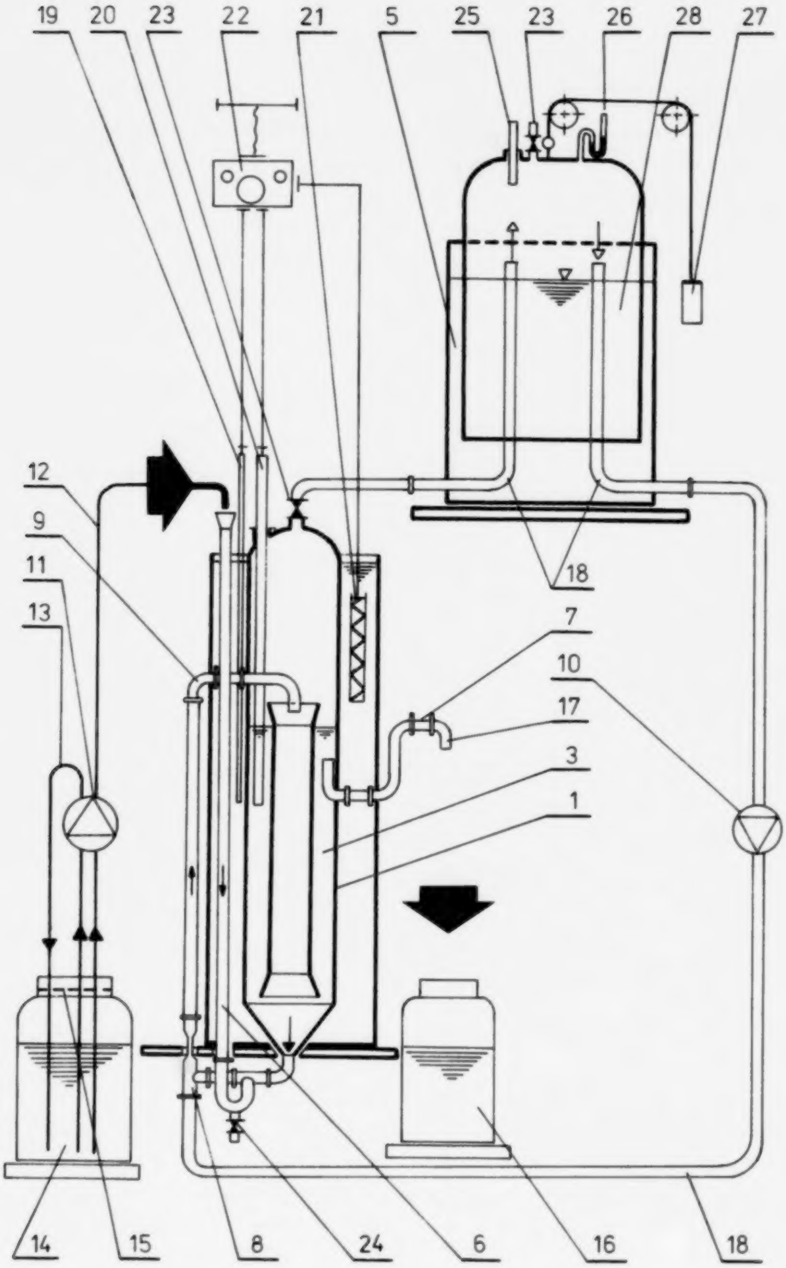

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Figure 45. Layout of the ANCONT anaerobic digester.

samples and venting. Mixed liquor samples were collected through valve (24). Reactor mixing is induced by gas compressor (10) through pipe (18) and jet mixer (8) as shown in Figure 45.

The overall volume of the reactor is 5.10 dm^3 of which approximately 35 percent is the volume of the gas mixed reactor. Since sludge wasting was not practiced, the total volume was used in the calculation, since removal and gasification occurred in the settling compartment as well. The only sludge evacuation mechanism was the effluent suspended solids.

Twelve runs were made. Each run encompassed, on the average, 14 individual analytical series performed every second day. Each series usually included analyses of both influent and effluent BOD_5 (nf, f), COD (nf, f), TS, TVS, NH_4^+, TKN, $N\text{-}NO_2^-$, NO_3^-, and pH. Additionally, MLSS and MLVSS and ANCONT pH were determined every fourth day, the sample was collected from valve (24) (Figure 45). The foregoing analysis is based on approximately 3000 individual data points. Arithmetic averages are reported in Table 12.

The experiment was started with HRT equal to 7.4 days, and the HRT was gradually lowered down. This report is written with data available for HRT as low as 0.5 days. First results of the tests with HRT = 0.25 days and 0.125 days indicate feasibility of methanogenesis, however, they could not be included in the report due to time constraints. In the continuation of this work (Project JB-5-534-7, reference 169) phase separation and multi-stage anaerobic processes will be further evaluated.

Results and Discussion

The ANCONT reactors were operated without intended sludge wasting; sludge carryover was responsible for partial evacuation of excess sludge. The concentration of MLSS (X) and MLVSS (X_v) has gradually increased with the increased organic loading and decreasing HRT. The value of X_v has doubled from 15.4 to 34.6 g TVS/m^3, with HRT decreasing from 7 to 0.5 d, while the values of volumetric loading increased from 1.51 to 22.09 kg $TVS/m^3/d$ and 1.5 to 28.65 kg $COD_{nf}/m^3/d$. This indicated excellent liquifying potential of the ANCONT reactor even at very low retention times.

TABLE 12. SUMMARY OF THE ANCONT PERFORMANCE DATA*

HRT days Parameter	Unit	7.4	6.1	5.2	4.0	3.0	2.0	1.76	1.54	1.26	1.0	0.75	0.50
		1	2	3	4	5	6	7	8	9	10	11	12
SRT	d	36.8	30.6	25.1	20.2	16.1	13.2	12.4	11.0	9.9	8.5	7.2	5.0
pH	-	7.3	7.2	7.3	7.2	7.2	7.2	7.1	7.1	7.0	6.9	6.9	6.8
$COD_{nf}-S_o$	g/dm^3	14.27	14.64	14.27	14.64	14.27	14.64	14.48	14.48	14.48	14.23	14.36	14.33
$COD_{nf}-S_e$	g/dm^3	1.87	1.74	1.99	1.89	2.24	2.62	3.06	3.07	3.33	3.68	4.31	5.74
$TS - S_o$	g/dm^3	10.98	12.05	10.98	12.05	13.71	12.05	11.37	11.37	11.37	11.05	11.10	11.05
$TS - S_e$	g/dm^3	5.79	6.30	6.65	6.78	6.47	6.74	5.73	7.09	6.74	6.56	6.24	6.17
X_v	g/dm^3	15.40	15.45	18.94	19.06	18.00	21.30	24.90	29.14	30.73	33.85	32.90	34.60
$L-COD_{nf}$	kg/m^3d	1.96	2.40	2.76	3.61	4.71	7.21	8.23	9.41	11.59	14.22	19.17	28.65
GP	dm^3/d	1.90	2.28	2.48	2.90	3.35	4.07	5.11	5.62	6.22	7.06	8.02	9.21
CH_4	%	72.0	72.0	72.0	71.4	75.2	75.8	73.0	75.0	75.0	73.6	75.8	76.7

*Each number is the arithmetic average of 15 separate determinations which made up one run at a predetermined hydraulic retention time.

The laboratory scale ANCONT system with 5.1 dm^3 active volume required large volumes of wastes for feed at low HRT. The system was stable even at low retention times since sludge recycle allowed for much faster recovery from upsets and failures than in the ANFLOW reactor. As found by other authors, e.g. Lin Chou, Speece and Siddiqui (170), the increase in SRT over HRT has created an inherently stable system as compared to the ANFLOW type reactor.

The increase of SRT did not effect directly the organics removal efficiency. The value of SRT was directly related to HRT and exerted a much different effect on removal and gasification efficiency than the organics loading, the primary and direct factor of influence (Figure 46-A). Similar conclusions are drawn by Carr and O'Donnell (172), who have also found that the viability or bacterial activity of the digester solids is not directly linked to the TS concentration. In fact in their work, COD was better removed at lower TS, although the solids served as an excellent buffer against shocks and sudden load changes.

The initial concentrations of carbon and nitrogen in this study were 4600 mg/dm^3 and 830 mg/dm^3, respectively, a ratio of C:N = 5.54. Several authors indicate the need for maintaining the optimum ratio of at least 16:1 (173). On the other hand, recent studies of Sroczyński and Kokuszko (171) show that the differences in fermentation efficiency at optimum C:N (their optimum was found experimentally as 11.5:1) compared to the ratio they used to operate their system C:N = 6.5:1 was only 3 to 4 percent, expressed in terms of COD_{nf} removal.

The first graphical correlation from the data in Table 12 is presented in Figure 47 and shows effects of increased HRT on gas production, effluent quality and pH in the ANCONT reactor. It is characteristic that gas production from the unit ANCONT volume as well as the pH curves show abrupt change at HRT = 2 days, being formed of two straight lines of the $y = ax + b$ type. This finding may be compared with data from the ANFLOW studies where the linear increase in pH slowed abruptly at approximately HRT = SRT = 8 to 10 days. In the ANCONT study HRT = 2 days corresponds to SRT = 13 days. The correlation of pH versus SRT is presented in Figure 48-B.

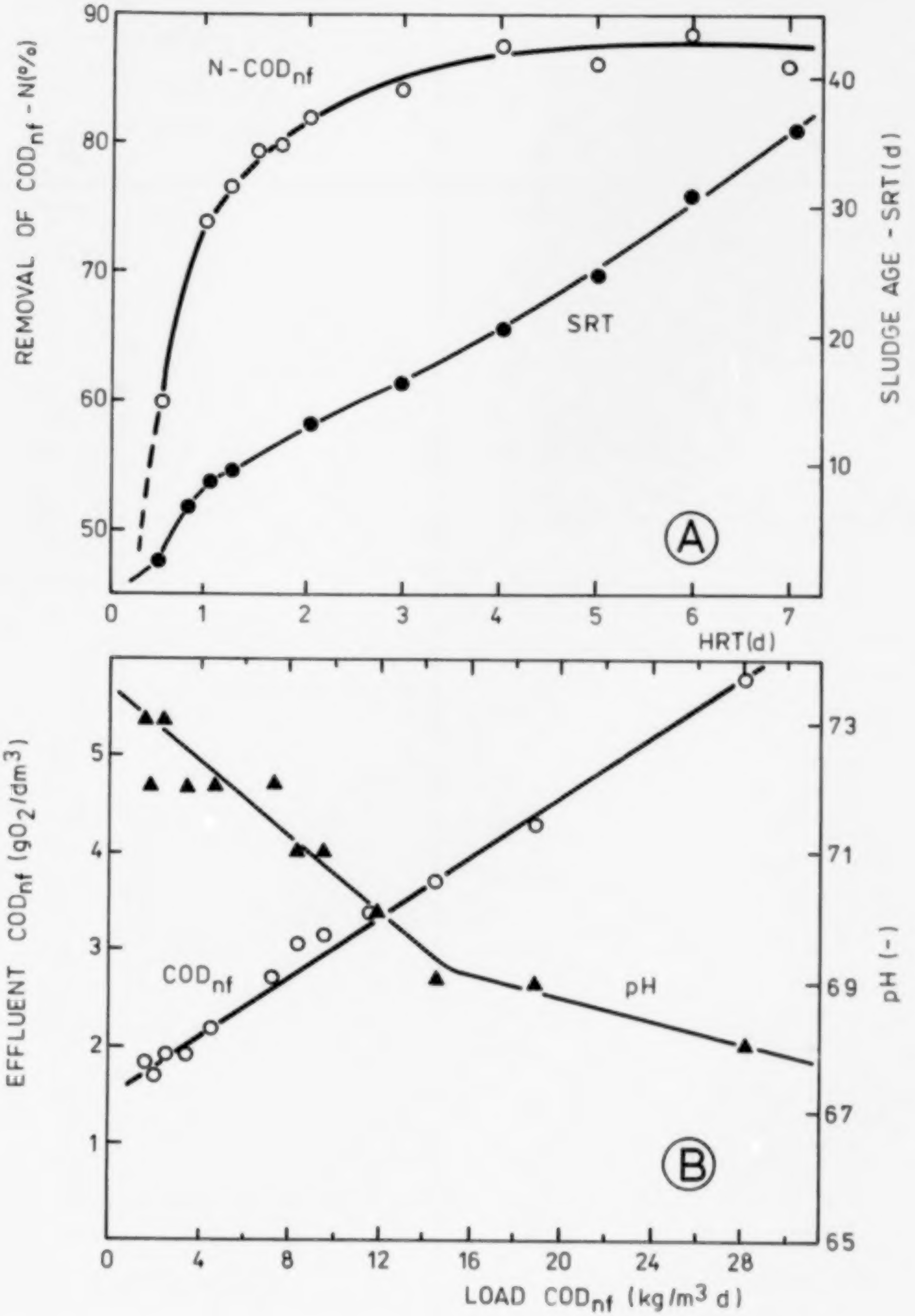


Figure 46. Effects of hydraulic retention and organic loading on SRT, ANCONT pH and effluent quality.

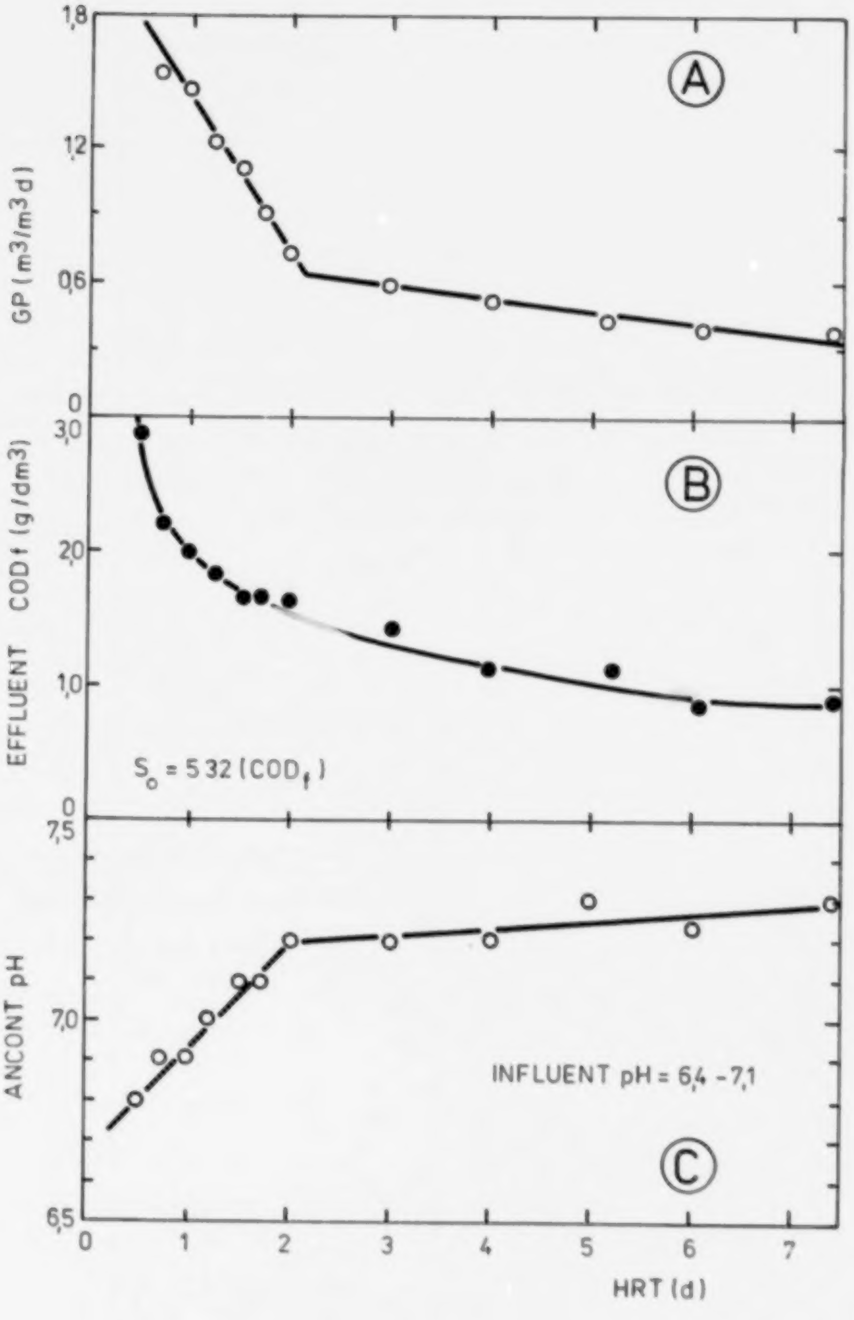


Figure 47. Effects of hydraulic retention on: (A) Gas production; (B) Effluent; (C) pH in the ANCONT reactor.

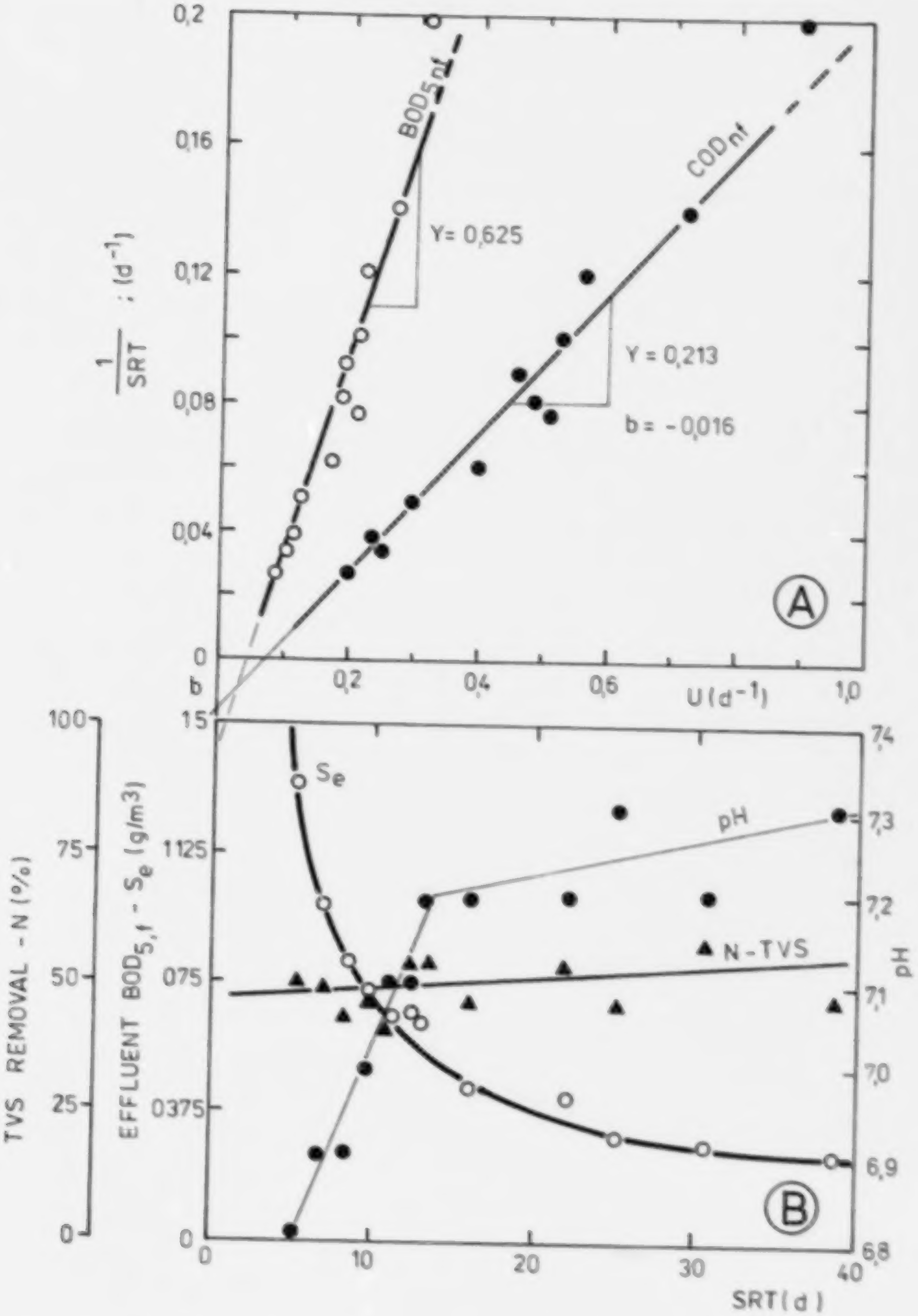


Figure 48. (A) Kinetics of organics removal; (B) Effects of sludge age (SRT) on effluent BOD and pH in the ANCONT reactor.

Gas production changes linearly with HRT until HRT = 2 days; then after an abrupt change in rate (see Figure 47-A), it decreases linearly following equation:

$$GP = 0.62 - 0.051 \text{ HRT}; \quad \text{for HRT} \geq 2 \text{ days} \tag{29}$$

The decrease of gas production with HRT is the result of decrease of organic loading introduced, which has a more profound influence than the increase of unit utilization of organic matter in the system, i.e., the more complete fertmentation at higher HRT.

Effluent concentration of organics evidences a hyperbolic decrease with HRT (Figure 47-C), similar to removal efficiency as shown in Figure 46-A which stabilizes at 87 percent COD_{nf} at HRT $\geq$ 3.5 days. The HRT in ANCONT should, however, be regarded as a supplementary design factor for volume determinations, since the major effects on effluent quality and gas production is exerted by organic loading. All subsequent correlations are against volumetric loading and/or SRT.

Figure 46-B illustrates a linear increase in effluent quality expressed in COD_{nf} with volumetric COD_{nf} load:

$$S_e(COD_{nf}) = 1.5 + 0.151 \text{ L} \tag{30}$$

Adequate accuracy is attained in this graph, however, one should bear in mind the fact that the concentration of biological solids in the reactor X_v (MLVSS) increases with the increase of L and that the removal efficiency is in fact affected by the food to microorganisms ratio (F/M) as in case of activated sludge. Similar accuracy is attained for COD_{nf} removal correlation in Figure 49-C:

$$COD_{nf}(\%) = 89 - 1.01 \text{ L} \tag{31}$$

The curve for effluent COD_f versus L (COD_{nf}) yields two straight sections; for L $\geq$ 4 kg/m^3/d:

$$S_e(COD_f) = 1.1 + 0.0618 \text{ L} \tag{32}$$

Beyond the inflexion point (L < 4 kg COD_{nf}/m^3/d), the line tends to go to zero which could indicate that almost all of soluble COD is biodegradable.

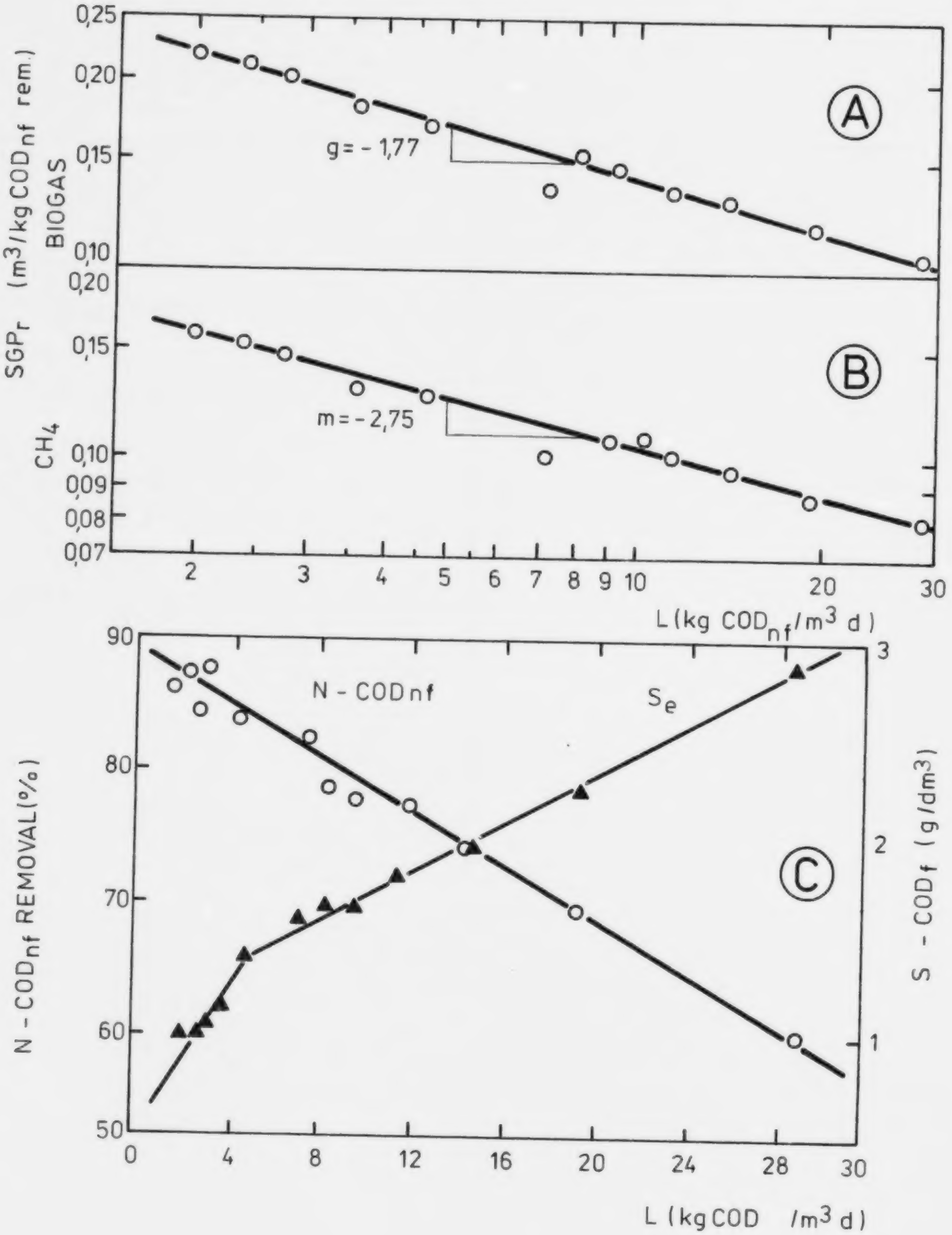


Figure 49. Gas production from removed COD_{nf} and efficiency of COD_{nf} removal in ANCONT reactor.

From Figure 46-B, it can be incurred that the nonbiodegradable COD is in the solid, non-filterable form and is equal to 1500 mg O_2/dm^3.

Figure 50 illustrates biogas production from the introduced COD_{nf} versus load, in arithmetic and log x log scales, indicating good approximation of the hyperbolic equation:

$$(COD_{nf})\ SGP_o = L^{-1.44} \tag{33}$$

Similarly in Figure 49-A and -B, very good fit is obtained for biogas and methane production from removed COD_{nf}:

$$(COD_{nf})\ SGP_r = L^{-1.77};\ \text{biogas} \tag{34}$$

$$(COD_{nf})\ SGP_r = L^{-2.75};\ \text{methane} \tag{35}$$

Comparing the efficiency of fermentation versus SRT with correlations versus COD load or HRT, it is evidenced in Figure 48-B that SRT exerts, similar to HRT, curvilinear effect on effluent quality expressed here as $BOD_{5,f}$. It follows from this graph that the fermentation of TVS, expressed as removal efficiency, stays steady at approximately 50 percent at SRT 5 to 40 days.

Kinetics--

The kinetics of biological growth from unit of removed substrate is presented in Figure 48-A. Equation 27 was applied, where the value of

$$q = (S_o - S_e)/(X_a.HRT) \tag{36}$$

The plot for COD_{nf} and BOD_{nf} data, with assumed active (viable) biomass concentration $X_a = 0.55\ X_v$/(equation 22) yielded the values of biomass yield coefficients Y(COD) = 0.213, Y(BOD) = 0.625 and the decay coefficients, b(COD) = 0.016 d^{-1}, b(BOD) = 0.026 d^{-1}. These are lower values than Y = 1, obtained from the ANFLOW study, however, errors are present here too, due to the already mentioned problems with X_v, X_a determinations.

Correlation by means of the Eckenfelder-Ford method (Equation 26) yielded values of Y >> 1. This could indicate inapplicability of standard biomass growth models to studies where the active (viable) biomass is not determined accurately and where there is little control on sludge recycle (sludge age).

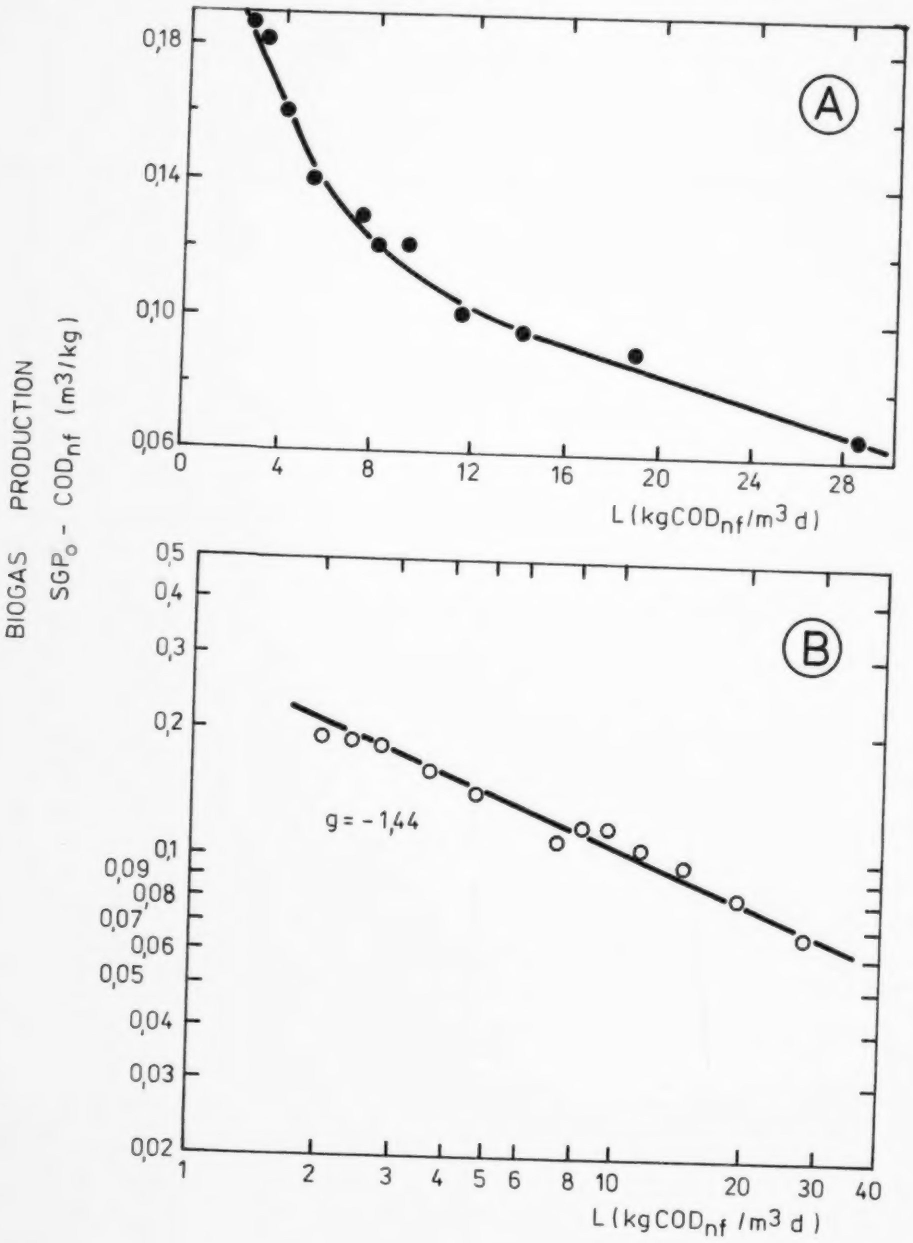


Figure 50. Kinetics of biogas production from the COD_{nf} introduced.

Finally, substrate removal kinetics was evaluated graphically, according to equation 1 modified for constant S_o:

$$\frac{S_o - S_e}{X_a . HRT} = KS_e \tag{37}$$

Figure 51-A and -B shows this correlation for COD_{nf} and $BOD_{5,f}$, respectively. The plot for COD_{nf} yielded $K = 0.09\ d^{-1}$. The values quoted by Oleszkiewicz, Koziarski, et al. (56) for various full scale activated sludge plants were $K = 1.70$ to $1.75\ d^{-1}$. The value for $BOD_{5,f}$ in ANCONT reactor was $K = 0.22\ d^{-1}$, while the aerobic activated sludge system removed $BOD_{5,f}$ with a rate coefficient of $K = 3.35\ d^{-1}$ (56). Based on the theory of biological treatment, it is known that aerobic processes are many times faster. Here the removal rate for activated sludge is 15 to 30 times higher than anaerobic contact digestion. However, due to technical constraints and other parameters imposed on aerobic systems such as permissible organic loading L and F/M, the resulting ANCONT volume should exceed the volume of an activated sludge tank (with the clarifier) only by a factor of three to four.

Discussion and Conclusions

The ANCONT reactor studies have shown that it is possible to decrease the anaerobic digester volume down to 3 to 4 days HRT. The reactor COD_{nf} loading at 4 days HRT can be as high as 4 kg $COD_{nf}/m^3/d$, yielding constantly, removals equal to or better than 85 percent COD_{nf}, and the following effluent qualities (averages of 15 steady state series) - values in mg/dm^3: $COD_{nf} = 1900$; $COD_f = 1200$; $BOD_{5,nf} = 700$; $BOD_{5,f} = 500$; and TVS = 4100.

The gas has a very steady methane concentration of 72 to 76 percent. The average gas production from the unit volume of the reactor decreases with the increasing retention time, and decreasing organic loading. At the design load of 4 kg $COD_{nf}/m^3/d$, the gas production is $GP = 3.15\ m^3/m^3/d$ (75 percent CH_4). The unit or specific gas production from the introduced SGP_o at L = 4 kg $COD_{nf}/m^3/d$ equals: $SGP_o - COD_{nf} = 0.18\ m^3/kg$; $SGP_o - BOD_{5,nf} = 0.35\ m^3/kg$; SGP_o - TVS = $0.25\ m^3/kg$.

The respective specific biogas production from the unit of SGP_r, at L = 4 kg $COD_{nf}/m^3/d$ equal to 0.17 $m^3/kg\ COD_{nf}$, 0.51 $m^3/kg\ COD_f$, 0.41 $m^3/kg\ BOD_{5,nf}$,

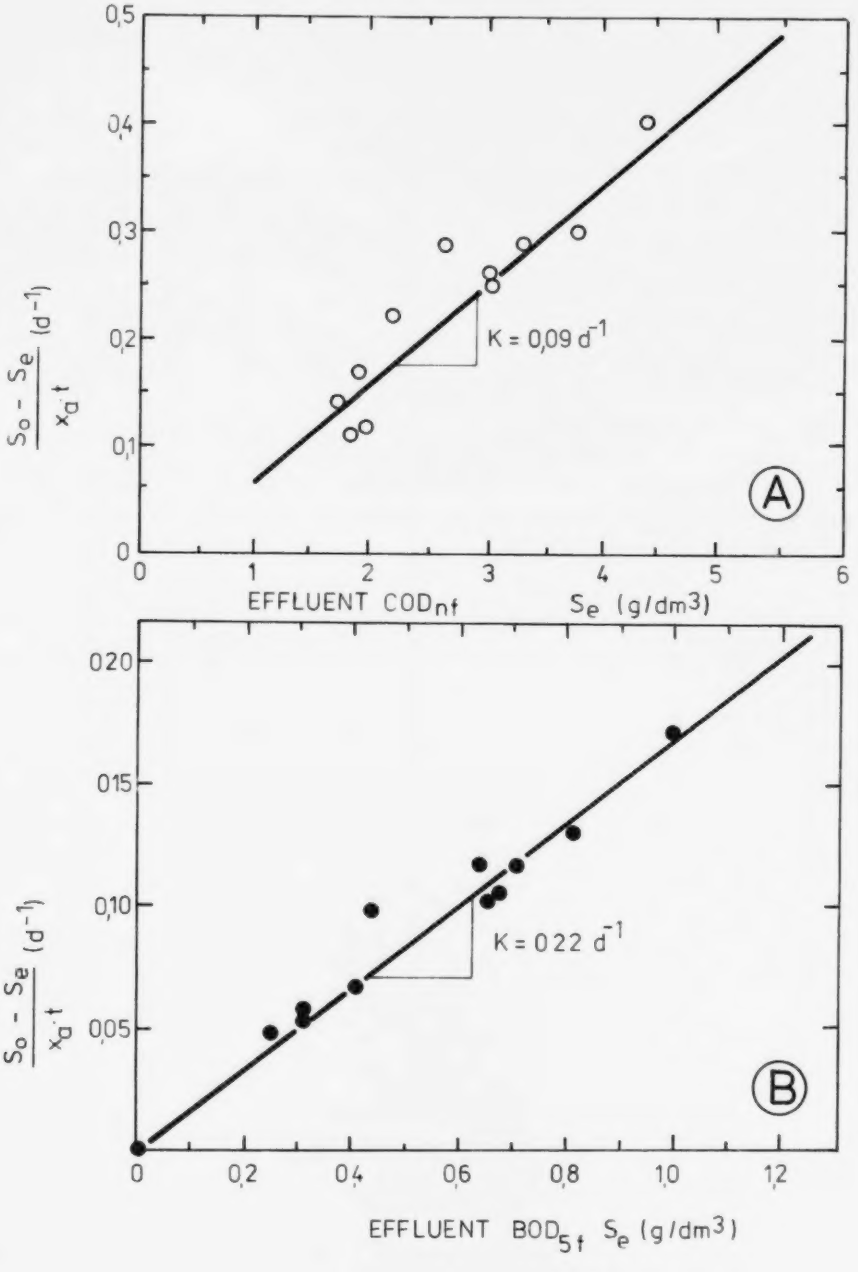


Figure 51. Kinetics of $BOD_{5,f}$ and COD_{nf} removal in ANCONT reactor.

0.74 m^3/kg $BOD_{5,f}$, 0.34 m^3/kg TS, and 0.5 m^3/kg TVS. These values correspond to an approximate production of 2.20 m^3 biogas/m^3 piggery wastes (75 percent) at HRT = 3.5 d and L = 4 kg COD_{nf}/m^3/d or 3.30 kg TVS/m^3/d or 3.8 kg TS/m^3/day.

These values are much lower than the values attained in the flow-through ANFLOW reactors (HRT = SRT) where SGP-COD_{nf} = 0.4 to 0.5 m^3/kg (SGP_o-0.3-036), at an optimum retention of HRT = 8 to 10 days.

It is concluded that the saving in construction costs of the volume of the ANCONT anaerobic digester is balanced by the lower gas production. The removal efficiencies attained in ANCONT reactors are much higher than those attained in the ANFLOW units. For the corresponding COD_{nf} load of 4 kg/m^3/d, the ANFLOW yields some 26 percent while ANCONT 85 percent COD_{nf} removal.

In both studies nonbiodegradable COD appeared to be equal to 1500 to 2000 mg/dm^3 and was in the non-filtered form (suspended solids and dispersed organic matter).

As in other anaerobic reactors, in this study the system with wastewaters exhibited good buffering capacity, the ANCONT pH was practically stabilized beyond 2 d HRT (SRT = 13d) at 7.2 to 7.3.

ANAEROBIC BIOFILTRATION IN ANBIOF REACTORS

Anaerobic digestion with suspended cultures of dilute wastewaters, i.e. with water content exceeding 98 percent, is usually difficult to achieve due to the washout of biota and difficulties in separating the secondary sludge. Frostell (1979) notes that the doubling time for methanogenic population tends to increase with the wastes becoming more diluted. Anaerobic biofilters offer an alternative to the sludge return (contact) system by providing supportive media for anaerobic organisms and thus, effectively increasing the SRT over the usually short HRT.

The interest in anaerobic biofiltration has been recently activated by Frostell (48), Anderson et al. (49), Mosey (50), Genung et al. (51), Mueller and Mancini (88) and others, however, these authors used synthetic soluble wastes or effluents otherwise totally different from animal wastes, the latter were never before treated in heterogeneous-fixed film reactors.

The aim of this study was to define the feasibility of attaining high removal efficiency at low retention time and at low temperatures and high organic loadings in anaerobic biofilters (ANBIOF) treating raw-screened piggery wastes. It is expected to develop a treatment system characterized by lower initial costs and significantly reduced power requirements.

Methods

The experiments were conducted in laboratory conditions, at 23 to 26°C, in a setup as in Figure 52. Three filters were used in parallel. The ANBIOF 1 and 2 had ID 0.12 m bed height H = 1.90 m (liquid height 2.10 m) and overall volume V = 0.023 m^3, while ANBIOF 3 had ID = 0.010 m, H = 1.35 m (1.57 m liquid), and V = 0.011 m^3. The specific surface area of the media, which consisted of 20 mm expanded polyethylene spheres, was 100 m^2/m^3. Gas production was measured in brine filtered gas tanks since the methods of measuring through meters were discredited earlier, as unreliable for small gas volumes. The large gas tanks have also served as an equalization tank.

The studies were initiated after stable effluent quality was attained and after a time equal to five HRT had elapsed. The anaerobic processes were seeded several times with inocculum from batch digestion and contact digestion units. Analytical determinations included TS, TSS, VSS, DS, pH, alkalinity, nitrogen: $N\text{-}NH_4$, N_{org}, COD_f, COD_{nf}, $BOD_{5,f}$, and $BOD_{5,nf}$. All results in Table 13 are the average of ten determinations. Since each run encompassed some 200 individual analyses (10 analyses of 20 parameters), the foregoing analysis is based on 1800 data points. The samples were 24 hr average composites.

Gas analysis (Orsat method) included CH_4, CO_2, CO, C_nH_m, H_2, H_2S, N_2, and O_2 as a control for airtightness of the system. The reading of the accumulated gas volume was brought to STP conditions knowing the temperature, gas and barometric pressure.

Results

The studies have proved the expected reliability and efficiency of the anaerobic biofilters; the data is compiled in Table 13. The COD_{nf} removals

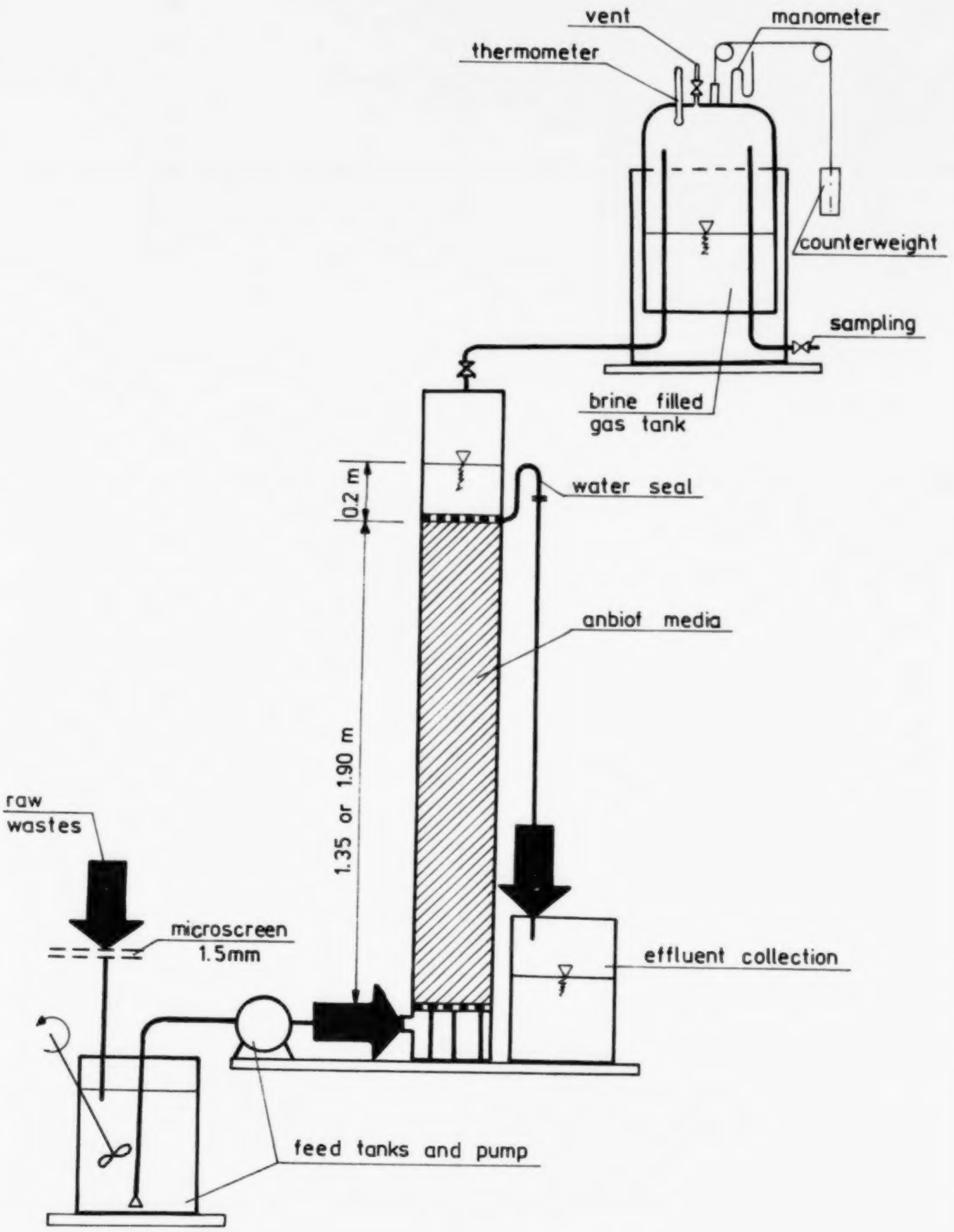

vent
manometer
thermometer
counterweight
sampling
brine filled gas tank
0.2 m
water seal
anbiof media
1.35 or 1.90 m
raw wastes
microscreen 1.5mm
effluent collection
feed tanks and pump

Figure 52. Layout of an anaerobic biofilter - ANBIOF - arrangement.

TABLE 13. RESULTS OF ANFLOW PERFORMANCE

Parameter	Unit	Loading with Non-Filtered COD kg/m^3/d							
		0.40	0.77	1.75	2.40	3.50	3.60	5.60	6.55
HYDRAULIC LOAD	m^3/m^3/d	0.04	0.08	0.17	0.25	0.36	0.34	0.61	0.74
HRT - (hydraulic)	hours	343	120	59.4	38.6	25.7	29.2	20.7	13.6
SRT - (solids)	days	698	497	211	66	57	52	46	34.6
S_o = COD_{nf}	mg O_2/dm^3	9,400	9,400	10,070	9,400	9,560	10,590	9,610	10,590
S_o = COD_f	mg O_2/dm^3	4,130	4,130	4,120	4,130	4,070	4,520	4,030	4,520
S_o = $BOD_{5,nf}$	mg O_2/dm^3	4,030	4,030	3,290	4,030	3,220	3,870	3.175	3,870
S_o = VS	mg O_2/dm^3	6,040	6,040	4,630	6,040	4,540	5,670	4,560	5,670
S_e = COD_{nf}	mg O_2/dm^3	660	570	1,080	2,130	3,070	2,340	3,020	3.170
S_e = COD_f	mg O_2/dm^3	300	320	570	1,050	1,420	1,090	1,610	1,680
S_e = $BOD_{5,nf}$	mg O_2/dm^3	210	300	705	710	1,220	930	1,120	1,405
S_e = $BOD_{5,f}$	mg O_2/dm^3	150	205	330	380	680	540	860	690
S_e = VS	mg/dm^3	1,020	800	680	1,210	1,310	1,360	1,040	1,630
CH_4 TOTAL production	m^3/m^3/d	0.009	0.067	0.103	0.242	0.366	0.358	0.642	0.499
CH_4 CONTENT	Percent	14.2	62.6	n.d.* (70)	76.6	77.8	80.4	n.d.** (80)	80.0

* n.d. (70) means "not determined," assumed equal 70 percent.
** n.d. (80) means "not determined," assumed equal 80 percent CH_4.

were 70 to 93 percent for HRT = 13.6 to 343.4 hr; has methane content increased with the decrease of HRT and the increase of the ANBIOF organic loading (L). Gas production was 0.024 to 0.172 m^3 CH_4/kg COD removed and 0.03 to 0.222 m^3 CH_4/kg TVS removed, at loadings from 0.4 to 6.5 kg COD/m^3/d.

The efficiency of COD_{nf} removal and effects of anaerobic biofilter volumetric loading on the basic process parameters, pH, alkalinity, and methane content are depicted in Figure 53. Figure 54 shows effluent total and soluble BOD_5 (A) and effects of loading on solids removed in Figure 54-B. The $BOD_{5,nf}$ removals were 64 to 95 percent yielding effluent quality $S_{e,nf}$ = 1400 to 210 mg O_2/dm^3.

The biogas composition has changed gradually versus the increasing COD loading, while the unit gas production has evidenced an increase with the COD load (Figures 55 and 56). The average daily methane production was 0.024 to 0.171 m^3/kg COD removed at the content of 14 to 80 percent (by volume) in the biogas. The long term gas production (based on storage in the gas tank) for the various ANBIOF units (three in parallel were used) showed differences.

Chmielowski's (53) conclusions that the duration of the acid phase of digestion can be minimized when soluble substrate able to enter cells for internal gasification to CH_4 and CO_2 is introduced, seem to be verified by this work. The low solids content of wastes at high loadings yielded efficient gasification at HRT. The methane generation rate was the highest at the lowest retention times equal to 12 to 24 hr, corresponding to the lowest organics removals.

The maximum methane generation rate observed was equal to only half of the theoretical maximum stoichiometric value of 0.35 m^3 CH_4/kg COD removed, which was easily attained in the anaerobic completely mixed reactors without sludge recycle. The authors see this as a result of lower temperatures of the biofiltration and the fact that other organisms are present in the biomass of the fixed film reactor when compared to classic conditions of the mesophillic methane generation at 35°C, in a completely mixed reactor.

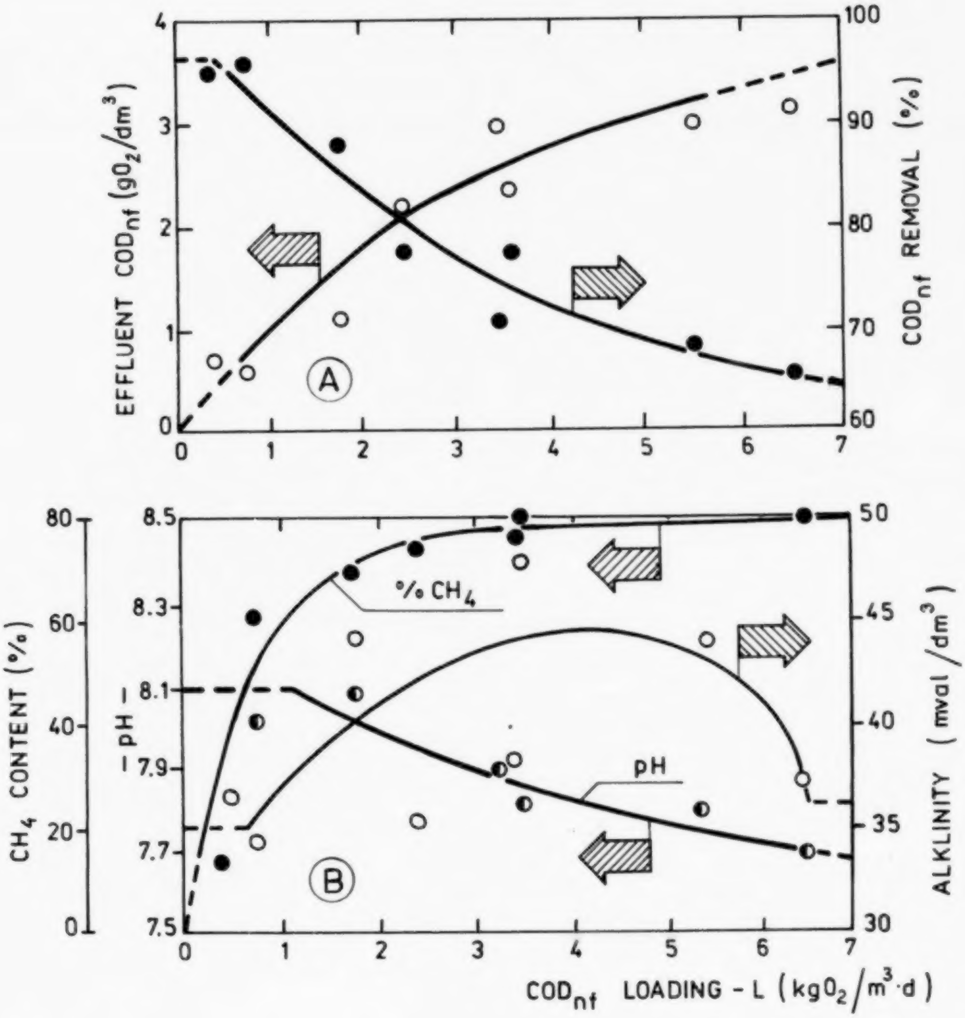


Figure 53. Effects of organic loading on: (A) COD_{nf} removal; (B) ANBIOF pH, methane content and alkalinity.

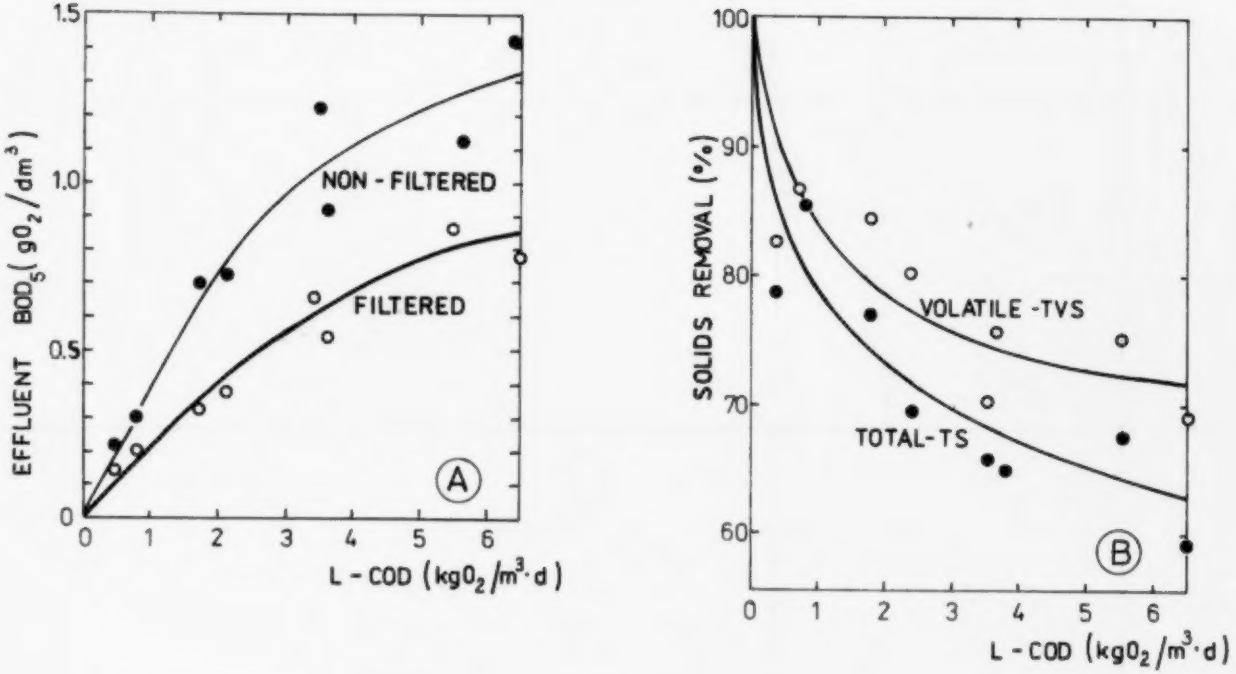


Figure 54. Effects of COD$_{nf}$ loading on: (A) Effluent quality; (B) Solids removal.

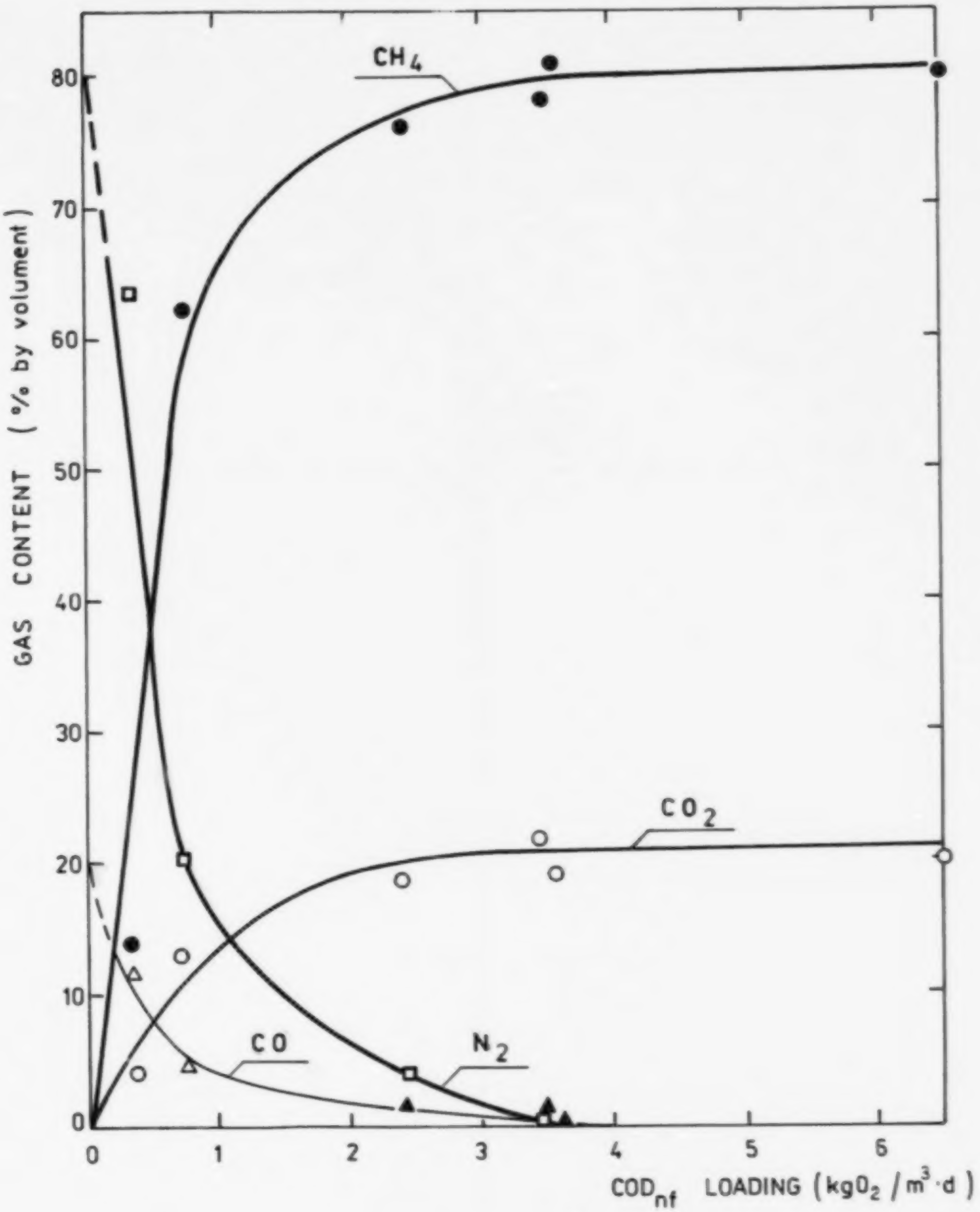


Figure 55. Effects of COD$_{nf}$ loading on composition of biogas from ANBIOF reactor.

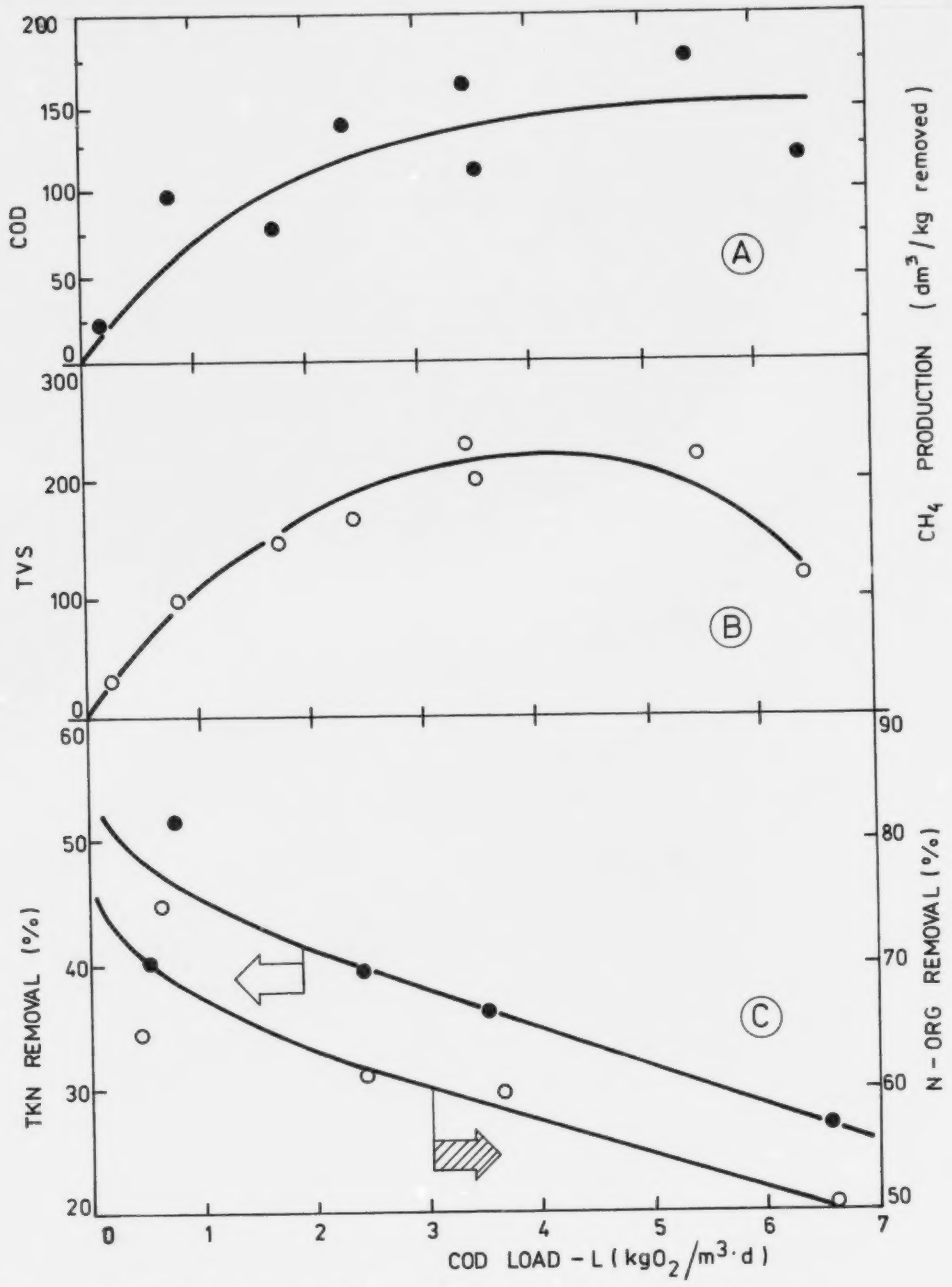


Figure 56. Effects of COD loading on CH_4 production from: (A) COD_{rem}; (B) TVS_{rem}; (C) TKN and N-org removals.

It is interesting to note in Figure 55 the presence of nitrogen and carbon monoxide at very long retention times and low loadings. The air contamination was excluded as oxygen was not found in the gas, and the gas composition is based on the average of three samples collected independently and denitrification processes occurring at the highest retention, i.e. at HRT above 1d or SRT above 50d.

The removals of TKN and organic nitrogen were respectively 30 to 50 percent and 52 to 72 percent (Figure 56-C). The increase of COD loading from 0.4 to 3.5 kg/m^3/d resulted in ammonia nitrogen removal 10 to 25 percent, coupled with nitrates removal (30 to 50 percent) and significant nitrite concentration increase (100 to 300 percent).

The studies on the breakdown of the stable digestion process showed that instability was reached at temperatures below 17^{o}C and at reaction variations beyond the easily tolerated range of pH = 6 to 8. The optimum process parameters were L = 2.5 to 4 kg COD/m^3/d, HRT = 24 hr, SRT above 50 days. The effects to be expected are methane generation rate of 0.160 m^3/kg COD-removed, some 70 percent COD removal which means S_e = 1500 mg O_2/dm^3 (COD_{nf}) for Farm A wastewaters.

Comparison of results of the direct aerobic treatment in one-stage activated sludge with the ANBIOF units performance, performed in another phase of the project, indicates that anaerobiosis breaks down complex and hardly biodegradable aerobically substances. The lowest concentrations of COD attained in the course of anaerobic biofiltration were 300 to 570 mg O_2/dm^3, while activated sludge yielded effluent 460 to 730 mg O_2/dm^3 (based on COD). It seems that anaerobic treatment is the best method of breaking down complex substances facilitating at the same time rapid and more complete aerobic polishing treatment.

Treatment Kinetics

Two first order equations were used to determine the rate of organics biodegradation:

$$S_e/S_o = \exp(-K\ HRT) \qquad (38)$$

and

$$S_e/S_o = \exp(-K\ SRT) \qquad (39)$$

where S_o, S_e are respectively the influent, effluent concentrations, K is the rate coefficient; HRT and SRT. The model derived by Oleszkiewicz (27) has also been tried:

$$S_e/S_o = \exp(-k/L) \qquad (40)$$

where L ($kg/m^3/d$) is the volumetric organic loading. The latter model yielded the most satisfactory fit (see Figure 57-A). Two phases of the process are distinguished from this plot. For COD_{nf} load above 2.0 kg $O_2/m^3/d$, the removal rate is 3.66 $kg/m^3/d$. Below that loading, the rate drops down to 0.42 kg $O_2/m^3/d$. The two rate constants were identical for the non-filtered and filtered COD data. The respective removal rates (k) expressed per unit area of the media surface (A) are equal to 20.0 and 4.2 g $O_2/m^2/d$ COD (K=kA).

Similarly, the plots of log S_e/S_o versus HRT yielded two rates $K_1 = 3.7d^{-1}$ and $K_2 = 0.21d^{-1}$, the change of rate occurred at HRT = 1.5 days. The log S_e/S_o versus SRT correlation has yielded $K_1 = 0.17d^{-1}$ and $K_2 = 0.002d^{-1}$, the rate changed at SRT equal approximately to 65 days (Figure 57-B). Interpretation of the log S_e/S_o against HRT correlation of data provided by Young and McCarty (54) has yielded similar results, however, the rate change occurred at HRT = 3.5d, probably because wastewaters were more diluted in their study.

Discussion

The results indicate that the ANBIOF system of contact digestion with attached biological slime is capable of treating piggery effluents with low solids content. The development of adequate microorganisms composition in the slime at temperatures of 20°C to 25°C, i.e. lower than the optimum mesophyllic range (35°C) can be achieved only after prolonged adaptation. With large multiple seedings done with actively digesting mesophyllic cultures, the break-in was 100 to 120 days. Without seeding, the spontaneous optimization of the bacterial composition took several months.

After attaining stability, the system was resistant to short-term temperature changes within 20 to 25°C, to pH variation within 6 to 8, and organics concentration variability. It is interesting to note that Mueller and Mancini (88) in their study of highly loaded anaerobic biofilters have found small

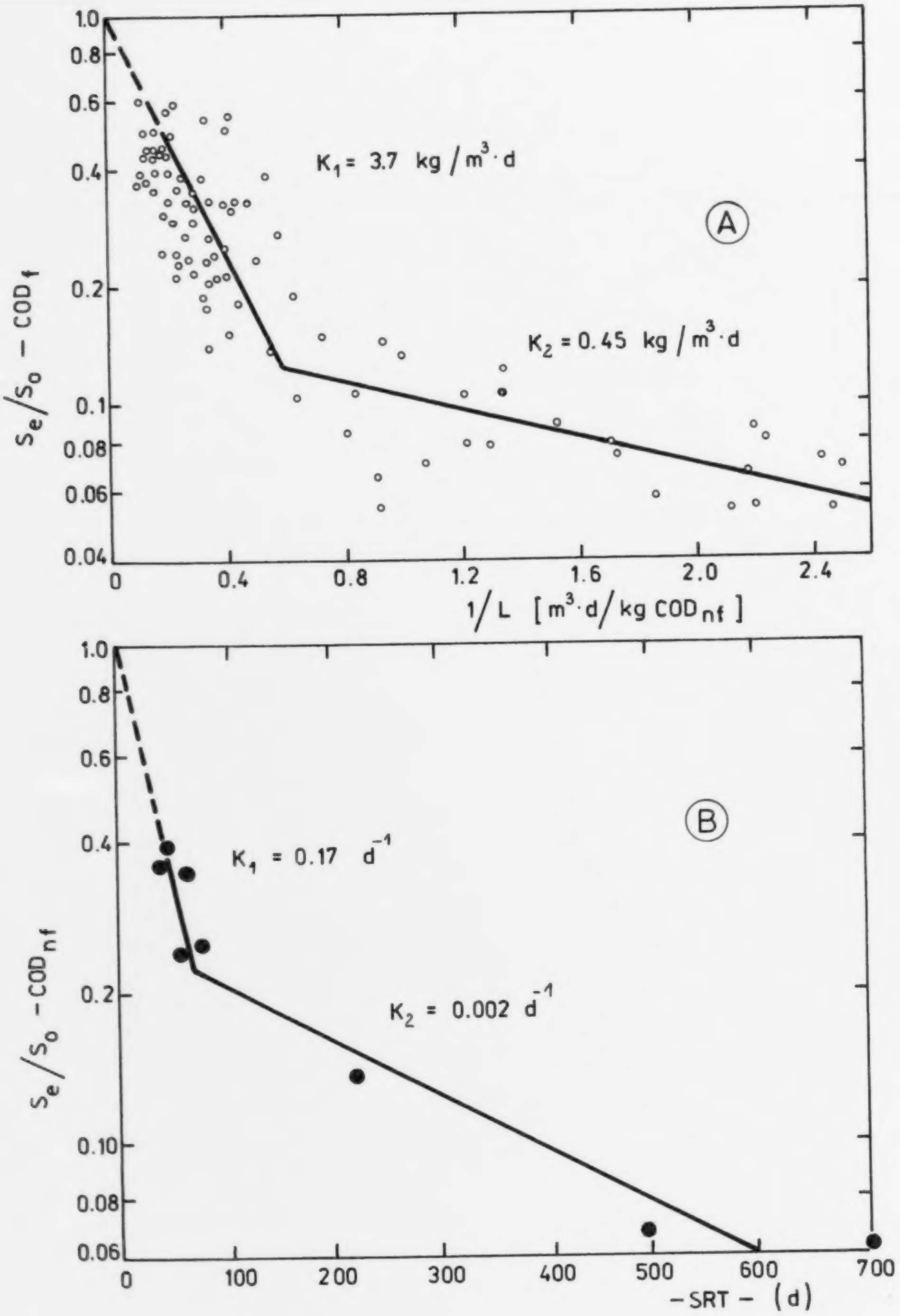


Figure 57. Kinetics of COD$_f$ removal in ANBIOF: (A) Pseudo-first order reaction; (B) Against sludge age SRT.

differences in removal rates at temperatures 25°C and 35°C for acidogenic phase and no difference for methanogenic phase.

Due to the alkalinity of piggery wastes equal to 25 to 70 $mval/dm^3$, the ANBIOF units exhibited significant buffering capacity at all loadings, in our studies.

The studies in this proejct have also indicated that change of substrate structure occurring during anaerobic degradation makes the process an ideal alternative to physicochemical pretreatment before aerobic polishing treatment. Lower gas production attained with the anaerobic filtration is offset by the lower temperature requirements, lower maintenance requirements, and high removal efficiency.

The data by Frostell (48) and van den Berg and Lenz (139) indicate that the type of media and mode of application have a small effect on removal efficiency. These conclusions supply the author's contention (94) that efficiency of biological removal is dependent primarily on sludge loading. However, the results of these studies show that in upflow ANBIOF unit most of the removal takes place in the first 30 percent of the ANBIOF height. The control sampling revealed that COD_{nf} at H = 0.25 m measured from the inlet at the bottom of ANBIOF was close to 200 g/dm^3 due to the fact that there was a large biomass of suspended microorganisms. The nonfiltered COD gradually decreased every 0.5 m to 45 g/dm^3, 6 g/dm^3 and 2 g/dm^3 (ANBIOF 3) which indicated that the conditions in an upflow ANBIOF resembled more closely the fluidized bed principle than the classic concept of fixed film reactor. Thus, the type and the specific surface of the media have less importance than in aerobic trickling filters, where the hydraulic regime and media porosity decide whether aerobiosis or anaerobiosis are the dominant organic removal pathways. Anaerobic conditions may dominate in case of ponding and overgrowth of biological slime in aerobic trickling filters.

The kinetics of biochemical changes in the ANBIOF units are best expressed with a pseudo first order model $S_e/S_o = \exp(-K/L)$ or by $S_e/S_o = \exp(-K.SRT)$. The efficiency of treatment is dependent primarily on the volumetric loading and influent concentration. The relationship in Figure 58 shows the response of anaerobic biofilters to COD loading as reported by different authors for different effluents, against the data from this study.

Conclusions

The design criteria for anaerobic biofilters treating piggery wastes are as follows: for S_o (COD_{nf}) = 12,000 mg O_2/dm^3, S_e (COD_{nf}) = 1,500 mg O_2/dm^3 at L = 2.5 to 4.0 kg $COD_{nf}/m^3/d$, SRT = 56 d, HRT = 1d, and methane generation approximately 0.16 m^3 CH_4/kg COD removed. For the studied piggery effluent some 70 to 90 percent COD_{nf} removal can be attained during HRT = 15 to 60 hours, at 20 to 25°C. The COD_{nf} load removal rate expressed per unit area of the media (in the recommended operating range of the ANBIOF) is 20 g $O_2/m^2/d$ and per volume of ANBIOF 3.66 kg $O_2/m^3/d$.

Anaerobic biofiltration should be more widely accepted as an alternative treatment characterized by high efficiency of removal, good organic load shock tolerance, ease of maintenance, low land surface area requirements, energy generation potential, ability to operate at temperatures lower than the standard mesophyllic range, the 20 to 26°C temperatures can always be provided by low parameter waste heat at any industrial plant. The ANBIOF reactors is particularly well suited for soluble organic effluents with TS content below 0.5 percent.

In this study the anaerobic biofiltration has been proved applicable to both roughing and polishing treatment indicating very large flexibility of the basic operational parameters, i.e. organic and hydraulic loading.

DISCUSSION AND CONCLUSIONS

The various processes studied have shown that the piggery wastewaters are easily biodegraded anaerobically, with no lower TS concentration limiting the process performance. The anaerobic process in general, offers the best possible pretreatment before aerobic polishing treatment and before agricultural utilization. In the latter case there is only 10 percent loss of TKN during anaerobic digestion and almost complete destruction of pathogenic organisms. The effluent is almost non-odors. All process modifications have exhibited resistance to shocks (introduction of air or load variation), the most rapid recovery was evidenced by the ANCONT reactor and ANBIOF, i.e. was increasing with the increase of SRT.

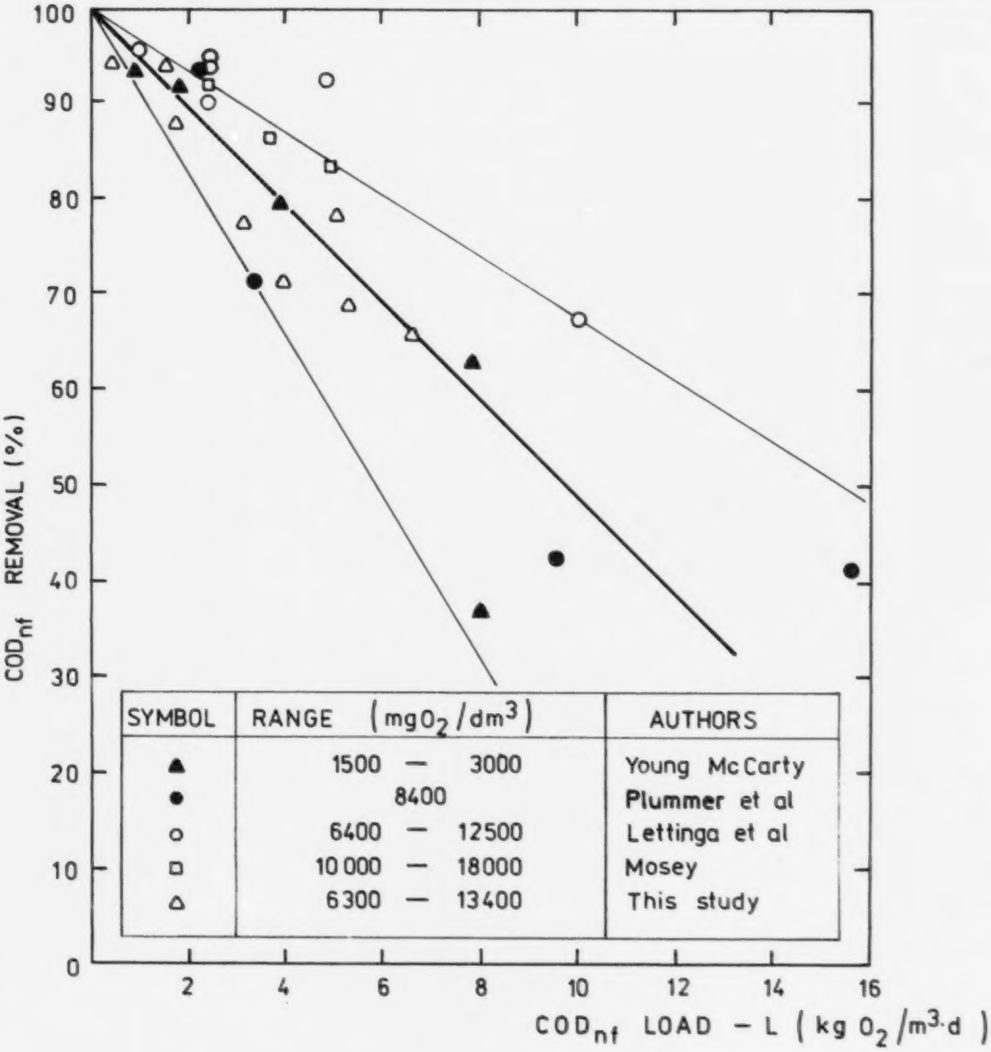


Figure 58. Operational range of ANBIOF reactors.

The studies have shown that the volume of the digester can be significantly reduced by increasing SRT through recycle or retention on the biofilter media. When one adds to this the value of recovered biogas, increasing with the ongoing energy crisis, the anaerobic digestion of dilute piggery wastewaters may become competitive to other methods of treatment.

Further studies are presently being conducted on possible further decrease of digester volume through phase separation and the increase of the overall organics removal rate, including nitrogen compounds, by combined anaerobic-aerobic-anaerobic systems.

Table 14 illustrates the performance parameters obtained in this study from the three basic anaerobic process modifications. It is interesting to note that anaerobic biofilter, ANBIOF, is much more efficient than an ANFLOW reactor and at the same time has a much smaller gas production rate, the latter increased with the increase of HRT and decrease of SRT. The increase of SRT has resulted in an increase of methane content in the biogas. Taking into account the design loads of the three reactors, the required volumes, the resulting effluent quality and the necessary level of maintenance, it is apparent that the anaerobic biofilter is the best system for dilute piggery wastes.

The dilution of wastewaters directly affects the selection of the process modification and the resulting economic implications. With the most concentrated animal wastes (TS above 2 percent) thermophilic digestion (55° to $60^{\circ}C$) in an ANFLOW type reactor may be feasible since the heat losses decrease with the decreased dilution, 90 percent of heat is required to heat up the incoming fresh wastes. In case of effluents with TS $\leq$ 2 mesophyllic digestion (30 to $35^{\circ}C$) in ANFLOW or ANCONT reactors is feasible. Lower concentrations of TS (below 0.5 to 1 percent) call for ANBIOF, i.e. heterogenous, biofilm reactors with well developed biomass, operating in the psychrophilic regime (15 to $25^{\circ}C$).

Since gas production in the homogeneous reactors, ANCONT and ANFLOW, is not completed, they should be followed by an ANBIOF reactor, which will benefit from the heat contained in the incoming wastes and yield much better gas production than those reported in Table 14. Studies, presently run by the authors (169), on two stage digestion, verify this hypothesis.

TABLE 14. COMPARISON OF OPTIMUM DESIGN PARAMETERS AND YIELDS IN ANAEROBIC REACTORS

Parameter	Units	Reactor			
		BATCH	ANFLOW	ANCONT	ANBIOF
COD_{nf} LOAD	$kg/m^3/d$	n.d.**	1.40	4.0	4.0
HRT	day	n.d.	9.0	4.0	1.0
SRT	day	n.d.	9.0	20.0	50.0
BIOGAS PRODUCTION*					
SGP_o - COD_{nf}	m^3/kg	0.36	0.29	0.15	0.13
SGP_r - COD_{nf}	m^3/kg	n.d.	0.60	0.17	0.17
SGP_o - TVS	m^3/kg	1.0	0.76	0.25	0.23
CH_4 CONTENT	Percent	n.d.	55.0	75.0	80.0
REMOVAL EFFICIENCY					
COD_{nf}	Percent	n.d.	63.0	85.0+	73.0
EFFLUENT COD_{nf}	g/m^3	n.d.	6.5	1.9	2.5
$BOD_{5,nf}$	g/m^3	n.d.	2.0	0.9	1.1
$BOD_{5,f}$	g/m^3	n.d.		0.44	0.67
RESISTANCE TO SHOCKS IN OPTIMUM CONDITIONS		+	++	+++	++++
EASE OF OPERATION		++++	++	+	+++

*The SGP values for ANFLOW reactor are SGP^a, i.e. are based on the ratio of total volume of gas produced to the total COD_{nf} or TVS load removed or introduced during the whole experimental run.

**n.d. - not determined.

The analysis of the overall design of a piggery wastes treatment plant revealed that the optimum system should feature high efficiency of wastewater treatment, sludge stabilization, high specific gas production and constant generation of anaerobic seed, a measure against sporadic disinfection practices and occasional antibiotic shocks. The system consists of a thickener which separates supernatant for anaerobic biofiltration and sludge for anaerobic digestion in a modified ANFLOW-ANCONT type reactor with additional clarifying sludge recycling facility and a HRT of 10 to 15 days. The digester receives sludge from the polishing treatment steps and discharges supernatant to the ANBIOF reactor system.

SECTION 9

PRODUCTION OF YEASTS

INTRODUCTION

Mounting protein deficit and difficulties encountered with conventional treatment of industrial piggery wastewaters or problems with the year-around agricultural utilization have directed the attention towards the possibilities of yeast production on these effluents for use as feed additive in feeding swine or other animals. Most of work published so far on yeast production from animal wastes has been confined to cattle wastewaters, Anthony (109), Calvert (112), and Singh and Anthony (120). The papers on yeast production from swine wastes show that researchers are looking for methods of enriching this substrate with easily available carbon and for more economical methods of substrate sterilization (113).

Yeast fermentation for SCP recovery has been extensively used by industry on such waste products as whey, molasses and sulphite liquors. Wastewaters from numerous food and organics processing industry plants have been successfully fermented by Candida utilis, Saccharomyces cervisiae, Trichoderma viride, Rhodotorula glutinis and other species in both laboratory and pilot scale by Tomlinson (122).

Concentrated piggery wastes have been fermented in laboratory, sometimes with the addition of cracked corn or with addition of other carbohydrate substrates such as sucrose in fungi fermentation by Aspergillus niger (123). Up to date there have been no data presented on fermentation of dilute piggery wastes.

The ultimate goal of the presented research is evaluation of economic feasibility of producing pig feed supplement consisting of yeast derived from the farm wastewaters through fermentation. The system, could perhaps close the nutrient cycle in the farm, and produce high quality protein and low concentration liquid effluent for stream disposal, after adequate polishing treatment.

The present work has been aimed at evaluating:

- feasibility of fermentation of dilute manure;
- eventual need for carbohydrate supplementation;
- selection of the group of the most promising organisms;
- delineation of further pilot scale research priorities;
- testing selected species in semi-dynamic and dynamic studies; and
- evaluating economic efficiency of yeast fermentation as a method of SCP recovery and wastewater treatment.

The studies were conducted on Farm A raw (screened) wastewaters in batch mode and in batch-fed semi-dynamic mode as reported exhaustively by the authors elsewhere (117 and 125).

BATCH STUDIES

Methods and Equipment

Initially, screening tests of a large number of yeast species obtained from the Institute of Fermentation Industry in Warsaw were performed. The tests consisted of growing yeasts on agar, solidified piggery wastes in microbiological vials. The four species selected from these tests were Candida tropicalis, strain 11 strain 8, Candida robusta and Candida utilis, strain 3. These species have proved their growth potential on the manure substrate while other species failed to reproduce. They are characterized by intensive growth rate and high protein content of good quality when grown in optimum conditions. It should be noted that other strains, such as Torula casei, Torulopsis candida or Rhodotorula glutinis have not survived the pig manure substrate. It is of interest also that the four selected species exhibited only 30 percent survival, as determined by Löffler blue staining vitality test.

Further screening of the initial preparation methods and species was performed in batch tests. These consisted of various methods of hydrolytic breakdown of cellulolytic materials to bring up the energetic potential of the piggery wastewater prior to fermentation. Since various authors recommend different variations of preparatory treatment (124), the following methods of hydrolysis were tested in the batch mode:

- Sulphuric acid hydrolysis (pH 1.0) at 1.5 atmosphere in an autoclave for 2 hours;
- Sulphuric acid hydrolysis at atmospheric pressure;
- Heating on boiling water bath for 2 hours; and
- Decanting the manure, evaporation, acid hydrolysis and dilution to previous concentration.

The preparation of manure through hydrolysis was aimed at increasing the carbon to nitrogen C/N ratio in respect to easily biodegradable carbohydrate carbon. In the batch tests that followed, hydrolysis was not used. The reason is evident when one compares the total sugar after preparatory treatment (Table 15) with raw untreated manure. The raw wastewater concentration of total sugars varied between 200 to 530 mg/dm^3 while hydrolysis by the various methods, outlined above, yielded total sugar content of 230 to 740 mg/dm^3. The addition of molasses of up to 2 percent boosted total sugars to over 19,000 mg/dm^3.

Because of these results, all subsequent work was done on untreated raw piggery wastewaters. As a routine, the wastewaters were brought to pH 5 to 5.5 with sodium hydroxide, put into 250 cm^3 beakers, sterilized, seeded with some 50 cm^3 of monoculture seed grown on brewery mash and incubated for 3 to 5 days in 30°C.

The beakers were aerated with warm air, through sterile cotton air filters, in thermostatic incubators. If foaming became excessive, a few drops of sterile soya oil were added (see Figure 59).

After incubation, the samples were centrifuged at 3000 rpm, cake was weighed, dried, ground, weighed again and analyzed. The weight of the centrifuged manure sludge from a sterile reference sample and of the seed was substracted from the total obtained in order to get the true net microbial mass yield; supernatant was also analyzed.

TABLE 15. RESULTS OF BATCH FERMENTATION OF RAW CENTRATE OF PIGGERY EFFLUENT BY YEAST OF CANDIDA TYPE

Parameter	Unit mg/dm^3 as	Untreated Wastes A	Molasses Enriched B	C.robusta 1		C.tropicalis 11		C.tropicalis 8		C.utilis 3	
				A	B	A	B	A	B	A	B
COD	O_2	4,136	19,666	1,382	5,821	1,270	7,738	1,382	8,656	1,428	13,318
TKN	N	650	1,348	261	496	261	373	250	550	276	739
$N-NH_3$	NH_4^+	288	500	219	76	193	45	183	78	186	103
$N-NO_2$	NO_2	t	t (trace)	t	t	t	t	t	t	t	t
$N-NO_3$	NO_3	1.1	16.4	t	t	t	t	t	30	t	35
N-Org.	N_2	421	848	68	420	68	328	67	472	91	736
$PO_4^{=}$	$PO_4^{=}$	453	464	303	17	232	30	284	26	236	175
Tot. P	P	966	1,037	575	78	812	37	265	65	838	284
Sugars	$C_6H_{12}O_6$	500	19,600	417	58	420	1,760	460	48	468	1,336
Removals of:											
COD	%			67	70	69	61	67	56	65	32
TKN	%			60	64	60	72	62	59	57	45
$N-NH_3$	%			24	85	33	90	36	73	84	36
N-Org.	%			84	50	84	61	83	44	78	13
Phosphates	%			34	96	49	93	37	94	48	62

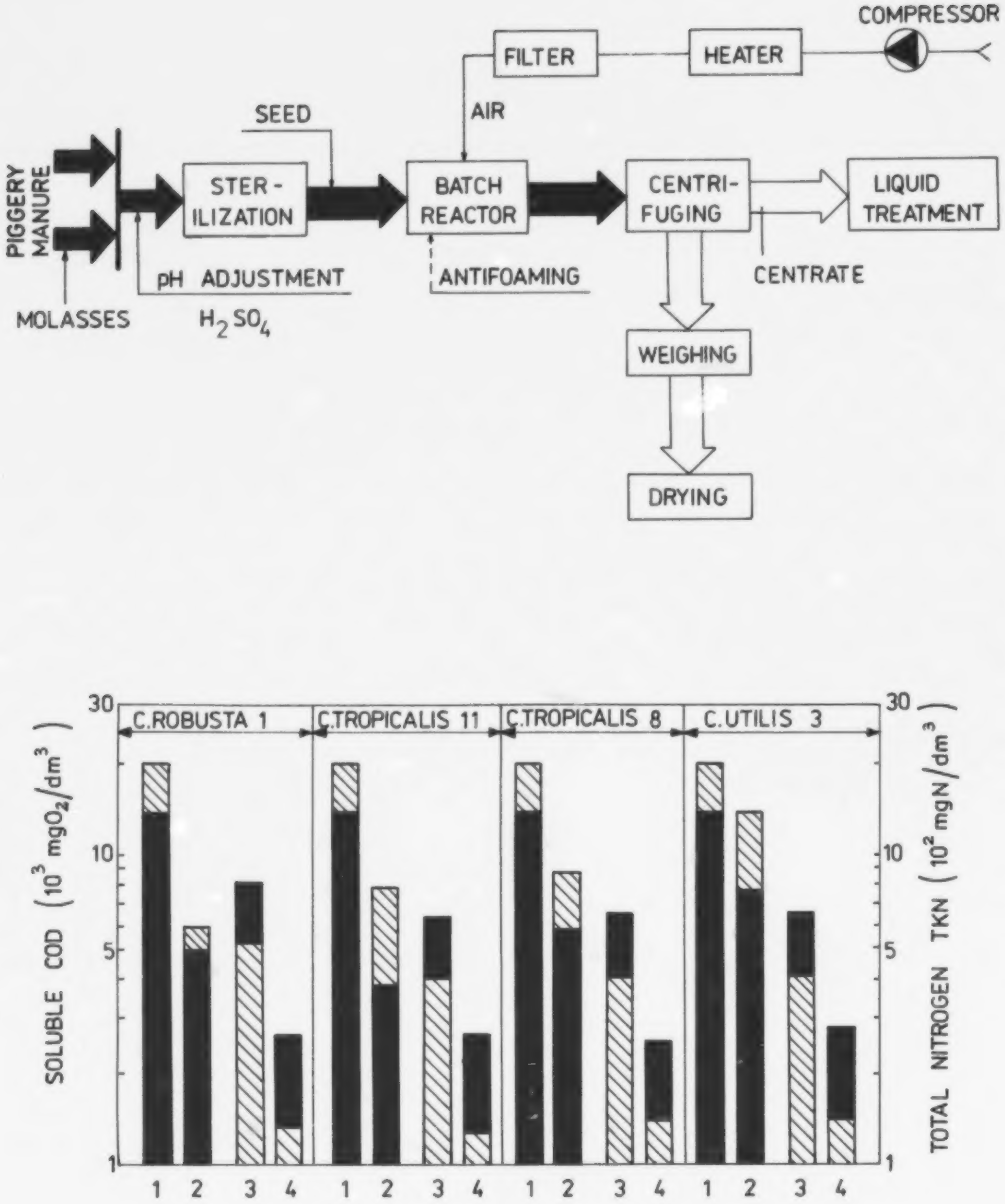

COMPRESSOR
FILTER
HEATER
AIR
SEED
PIGGERY MANURE
STER-ILIZATION
BATCH REACTOR
CENTRI-FUGING
LIQUID TREATMENT
pH ADJUSTMENT
ANTIFOAMING
CENTRATE
MOLASSES
H_2SO_4
WEIGHING
DRYING
C.ROBUSTA 1
C.TROPICALIS 11
C.TROPICALIS 8
C.UTILIS 3
SOLUBLE COD (10^3 mgO$_2$/dm^3)
TOTAL NITROGEN TKN (10^2 mgN/dm^3)
30
10
5
1
1 2 3 4

Figure 59. Batch yeast production studies: (A) Experimental set-up; (B) COD and TKN removals attained.

All analyses were performed according to the U. S. EPA guidelines or Standard Methods except for the colorimetric anthrone determination of the energetic material present, performed in accordance with Polish Standards PN-76/C-04628/02 and except for the vitality Löffler blue staining test.

Results

The following results are confined to the analysis of two substrates: raw untreated pig manure and raw untreated manure enriched with molasses both adjusted to pH 5.5. No hydrolysis was used for pretreatment because the process was considered not feasible in full scale.

The tests were run on two parallel batches of wastewaters with and without molasses each in four units to accommodate all four Candida type yeasts. The results of these eight combinations are presented in Table 15, which provides raw wastes centrate data, centrate (effluent) quality data and percent removals of individual parameters. Thus, Table 15 serves as an estimation of the potential of yeast fermentation in treatment of soluble fraction of piggery wastes. This is better illustrated in Figure 59 where influent and effluent COD and TKN concentrations are compared.

Table 15 shows raw and yeast treated centrate data because the only way to remove yeasts, commercially, would be by centrifuge. The tests were run on untreated total wastewaters. The cake from the centrifuge after fermentation consists of manure solids, seed solids and biomass culture. The actual values, compiled in Table 16 were calculated by subtracting from the total cake mass the masses of seed and the manure solids. The table also lists unit cells yield calculated from the difference between the influent centrate concentrations of nitrogen according to Kjeldahl method and carbon calculated **as 25 percent of COD and their respective effluent concentrations.**

Discussion

Results in Table 15 indicate good COD removals by all species of the Candida yeasts. The raw wastes COD removals oscillate closely in the range of 65 to 69 percent. The nitrogen removals expressed in TKN show a range of 57 to 62 percent, similarly N_{org} removal is stable. Phosphorus removals seem to favor C.tropicalis 8 (73 percent) and C.robusta 1 (40 percent) against C.tropicalis 11 (16 percent) and C.utilis 3 (13 percent). C.utilis 3 shows good removal of N-NH_3 (84 percent). The data on fermentation of untreated raw wastes for soluble pollutant removal indicates the suitability of the first two species mentioned.

TABLE 16. BIOMASS YIELD IN YEAST FERMENTATION

Yeast	Yeast yield kg d.w./m^3		Unit cells yield kg cells/kg nutrient removed					
			Nitrogen		Carbon		Phosphorus	
	Raw	Enrich.	Raw	Enrich.	Raw	Enrich.	Raw	Enrich.
C.robusta 1	2.13	5.86	5.5	4.6	3.1	1.7	16.6	18.7
C.tropicalis 11	2.22	7.58	5.7	5.8	3.1	2.5	44.4	80.0
C.tropicalis 8	2.74	6.11	6.8	4.8	4.0	2.2	12.0	19.0
C.utilis 3	2.05	2.85	5.5	2.3	3.0	1.8	49.0	8.4

NOTE: "Raw" refers to filtered raw wastewaters. "Enrich" refers to filtered raw wastewater enriched with molasses.

The data for enriched wastes clearly discriminates between the four species in favor of C.robusta 1 with the highest COD removal (70 percent) and constantly high removals of other nutrients, 64 to 96 percent. Definitely second best seems to be C.tropicalis 11, followed by C.tropicalis 8, while C.utilis yields the poorest removals, 13 to 73 percent.

Analyzing the batch fermentation from the biomass production angle, in Table 16, it becomes apparent that the two C.tropicalis give the best cell yields in both raw (2.22 and 2.74 kg dry weight/m^3) and in enriched wastes. The interpretation of unit cells yield reveals much better utilization of nitrogen, carbon and phosphorus in case of raw wastes. This means that enrichment with molasses does not improve the unit yields, i.e. kg cells/kg N, P, C removed, and that it leaves a considerable energy potential in the soluble centrate in all cases exceeding the raw centrate COD value.

An important point should be stressed here, namely the initial ratios C/N = 1.7 and C/P = 11 and for enriched C/N = 3.64 and C/P = 32.7, are much below the average optimum ratios practiced in the fermentation industry. The reason lies in the unusually high nitrogen and phosphorus content of piggery wastewaters, and leads to the contention that without carbon enrichment, yeast fermentation will always retain a lot of nutrients in the soluble effluent.

The analysis of data in Table 16 indicates a somewhat better performance of Candida tropicalis strains 8 and 11 over C.robusta 1 and C.utilis 3, both on enriched and raw wastes. The unit cells yield more and favor the two C. tropicalis strains, however, the margin is not large.

Preliminary estimates of protein content reveals dry weight protein content from approximately 46 percent for Candida utilis 3 to over 60 percent for C.tropicalis 11. The protein content was calculated by multiplying the TKN content by 6.25.

Conclusions

1. The preliminary hydrolysis to increase the carbohydrate content of piggery wastes proved ineffective and will not be feasible in full scale.
2. The solidified substrate tests have screened out four Candida type strains: C.robusta 1, C.tropicalis 11 and 8, C.utilis 3.
3. The batch liquid fermentation for 120 hours at an optimum pH 5.5 yields good removals of COD from the soluble fraction of wastewaters, i.e. 65 to 69 percent for all species and TKN removals of 57 to 62 percent, for raw wastes without enrichment.
4. The enrichment of piggery wastewaters results in:
    a. production of biomass apparently more lively than raw unadjusted wastes;
    b. production of larger biomass yield (kg/m^3), however, at the overall lower efficiency expressed in (kg cells) kg nutrient utilized; and
    c. increased removal of nitrogen and phosphorus from soluble effluent.
5. The results indicate also that enrichment with molasses may be economically difficult to justify, because:
    a. enrichment does not increase the unit cells yield per nutrient utilized;
    b. it retains considerable concentration to residual COD and certain amount of nutrients; and

   c. technical cost of supplying waste molasses may become forbidding, since it may be used directly as feed.

6. Considering the influent and effluent C/P, C/N ratios and their respective changes, it is concluded that raw, filtered piggery wastewaters are an unbalanced medium for aerobic aseptic fermentation.
7. The biomass of all yeast species, after drying and grinding, reveals no trace of specific pig manure odor.
8. Out of the four screened species, the Candida tropicalis 8 was the most suited for piggery wastes treatment and biomass production, while Candida utilis 3 showed the poorest performance based on batch tests.
9. Preliminary contents estimation in the dry biomass reveals high protein content ranging from 46 to 61 percent, dry weight.

DYNAMIC STUDIES

The batch tests have shown inadequacy of the presently available methods of pretreatment to increase the available carbon content. It has been found in this work that acidogenic anaerobic digestion yields an increase in the volatile acids content up to 10,000 mg/dm^3. Evison (114) expects to attain the values as high as 20,000 mg/dm^3. Due to the lack of space in this project, the system: anaerobic acidogenesis, yeast fermentation will be studied separately in the future. The subsequent work is on untreated pig wastes from Farm A, with and without addition of sucrose or sugar beet molasses (the solids were removed by screening).

Materials and Methods

The studies were conducted on fresh piggery wastewaters, stored for 12 hours in 10 to 12°C and then centrifuged for 10 min at 1500 rpm.

Four yeast species selected on the basis of batch tests were used: Candida tropicalis 8, C.tropicalis 11, C.robusta and C.utilis 3. When tests with carbon enrichment were run, then 10 percent water solution of sucrose or beet molasses diluted to 10 percent, by weight, of sucrose were used. Correction of pH was 1 Molar NaOH and 0.5 Molar H_2SO_4.

Yeast production was conducted in a 3 dm^3 active volume fermenter at a constant air flow of 40 dm^3/hr, mixed at 500 rpm, at pH = 5.0 and at 30°C as shown in Figure 60.

The growth of yeast was limited by the quantity of easily available carbon. The tests were concluded as follows: the fermenter was filled with filtered raw piggery wastes (1.5 to 2.0 dm^3 of wastes) and yeasts were added. Partial dissolved oxygen (DO) pressure was measured. When the oxygen demand by yeasts dropped, DO went up to 70 percent saturation, an aliquot of fresh substrate was added automatically. The process DO controlled as described by Miskiewicz et al. (115) and Robinson (119). In the test on wastes without enrichment, at the DO meter signal 0.1 dm^3 of wastes were added, until the liquid volume of V_t = 2 dm^3 was reached (V_o = 1 dm^3).

In the tests with sucrose the initial volume was 1.5 dm^3, the DO sensor activated the sucrose feed tank until there was an inhibition of the biomass growth.

In the tests with sugar beet molasses V_o = 1.5 dm^5, the tests were terminated after 7 hours in order to keep the length of the run comparable with the previous tests, thus, the final volume of approximately 2 dm^3 was dependent upon the amount of 10 percent molasses solution added.

The following analyses were performed on both raw and treated effluents: COD, TKN, $N\text{-}NH_4$ by colorimetric nesslerization; $N\text{-}NO_2^-$ colorimetrically with sulphonyl acid and naphtylamine, $N\text{-}NO_3^-$ colorimetrically with phenylbisulphonyl acid, $P\text{-}PO_4^{-3}$ colorimetrically and SOC.

Dissolved oxygen or O_2 was measured potentiometrically by means of a membrane DO sensor, as described by Borkoński et al. (110), while yeast content was evaluated turbidimetrically, as described by Miśkiewicz (115). Total protein content was determined in yeast cells as described in Methods in Microbiology (107); the amino acid AA composition was determined, after 20 hours hydrolysis (6 N KCl at 105°C) by a Czech AA analyzer.

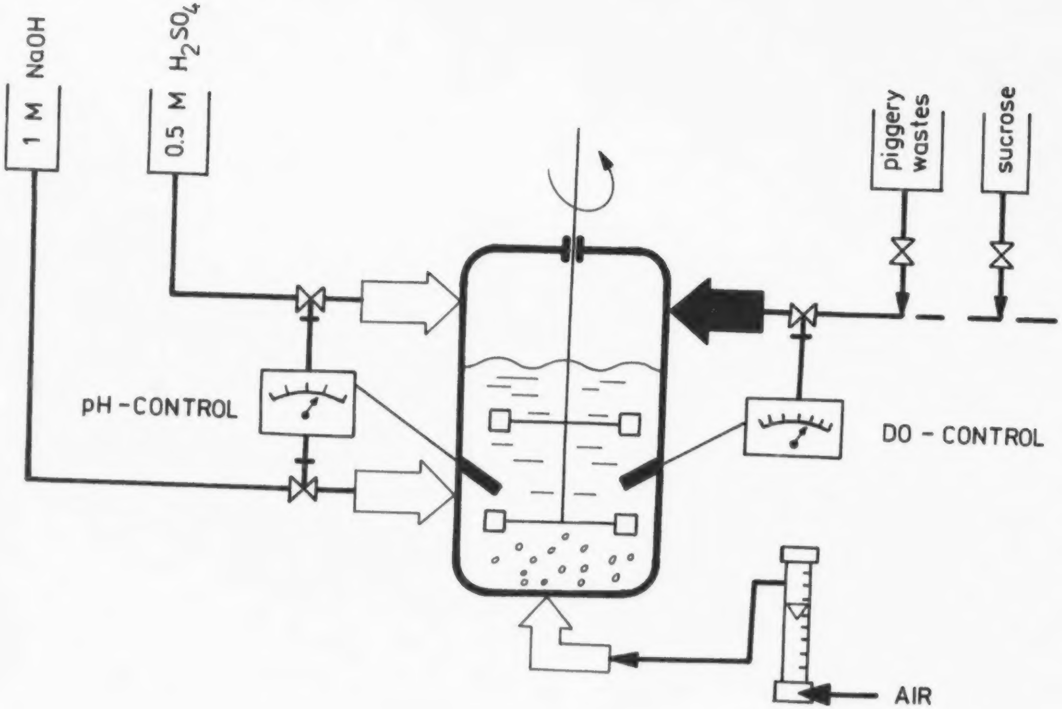

1 M NaOH
0.5 M H_2SO_4
piggery wastes
sucrose
malasses
pH-CONTROL
DO - CONTROL
AIR

Figure 60. Semi-dynamic yeast fermentation equipment.

The observed growth yield was calculated as:

$$Y = \frac{\Delta X}{S} \tag{41}$$

where: Y - observed growth yield (g/mole)

S - assimilated carbon (mole glucose)

ΔX - net biomass solids increase (g)

Results and Discussion

Tests with raw wastes without enrichment--

The time needed for assimilation of available carbon in 2 dm^3 of piggery wastes, without carbon addition, varied from 2 hr for C.tropicalis 8 and C.robusta to 3 hr for C.tropicalis 11.

The biomass increase was small and amounted to 0.385 g/dm^3 for C.tropicalis 8 and 1.395 g/dm^3 for C.utilis 3 and corresponded to the generally low productivity of 0.192 g/dm^3 hr for C.tropicalis 8 to 0.51 g/dm^3 hr for C.utilis 3 (see Tables 17 and 18).

Table 18 describes also the utilization of carbon, phosphorus and nitrogeneous compounds which were best utilized by C.robusta. This finding is coincidental with the results of batch tests reported above. The TKN removals in this study were 64 percent (60 percent in batch tests), where $N\text{-}NH_4$ decreased by 37 percent and $N\text{-}NO_2$ by 72 percent, with simultaneous increase of the nitrates from 11 to 15 mg/dm^3 $N\text{-}NO_3^-$. Phosphate removals were low, some 18.6 percent (and also low in batch tests, 34 percent) while COD and SOC removals were only 24 percent and 35 percent, respectively.

The C.utilis 3 species has removed 64 percent SOC while C.tropicalis 8, 58 percent, however, the TKN removals by these species were smaller than C.robusta, and amounted to 11.5 and 14.3 percent, respectively. Higher COD removals were obtained by the two species: 48 percent for C.utilis 3 and 59 percent for C.tropicalis 11.

These results show that yeast production on piggery wastes without carbon enrichment is at present not economical from the standpoint of biomass production. It is interesting to note that removal rates calculated from the formula:

TABLE 17. YEASTS' PRODUCTION ON FILTERED PIGGERY WASTEWATERS WITHOUT CARBON ENRICHMENT - REMOVAL EFFICIENCIES

	C.tropicalis 8		C.tropicalis 11		C.rubusta		C.utilis	
	Raw mg/dm^3	Removal (%)	Raw mg/dm^3	Removal (%)	Raw mg/dm^3	Removal (%)	Raw mg/dm^3	Removal (%)
COD	3,860.0	-	3,040.0	59.0	2,430.0	24.0	3,860.0	48.0
TKN	875.0	-	1,057.0	11.5	1,442.0	64.0	875.0	14.0
$N\text{-}NH_4^+$	400.0	-	370.0	23.0	342.0	37.0	400.0	25.0
$N\text{-}NO_2^-$	0.01	-	0.034	68.0	0.018	72.0	0.01	28.0
$N\text{-}NO_3^-$	5.0	-	13.0	increase to 28.4 mg/dm^3	11.0	increase to 33.8 mg/dm^3	5.0	increase to 27.0 mg/dm^3
$P\text{-}PO_4^{-3}$	736.0	-	680.0	8.0	860.0	19.0	736.0	3.4
SOC	800.0	-	1,125.0	58.0	850.0	35.0	800.0	64.0

TABLE 18. RESULTS OF YEAST PRODUCTION WITHOUT CARBON ADDITION - YEASTS YIELDS AND NUTRIENTS USE*

Parameter	Symbol	Units	C.tropicalis S	C.tropicalis 11	C.robusta	C.utilis
						fresh filtered
Initial yeasts	X_o	g DM	10.02	8.74	5.22	11.71
Net biomass increase	ΔX	g DM	0.77	1.96	1.06	2.79
Duration of experiment	t	hr	2.0	3.0	2.0	2.75
Maximum specific growth rate	μ_m	hr^{-1}	0.05	0.10	0.10	0.12
Productivity	P	$g\ DM/dm^3/hr$	0.19	0.33	0.26	0.51
Cell yield per nutrient used	Y	$\frac{g\ DM}{g\ nutrient}$				
Carbon		g/g C/hr	-	0.52	0.88	0.45
Phosphorus		g/g P/hr	-	10.2	1.65	31.7
COD		$g/g\ O_2/hr$	-	0.13	0.45	0.19
Average removal rate coefficient	k (SOC)	$10^{-3}dm^3/mg\ C/d$	-	1.0	1.0	1.0
Average removal rate coefficient	k (COD)	$10^{-3}dm^3/mg\ O_2/d$	-	1.1	0.6	0.6

*Wastewater volume 2 dm^3.

$$\frac{S_r}{(X_o + \Delta X)t} = k\ S_e \qquad (42)$$

where: S_r is the removed mass of pollutant including added carbon in test with enrichment (g),

S_e is the effluent concentration (mg/dm^3),

$(X_o + \Delta X)$ are the biological volatile solids (g DM); are comparable with removals attained in the activated sludge systems. As reported by Oleszkiewicz, Koziarski, et al. (11), this value for full scale systems was 200 to 400 mg/dm^3/hr, which is similar to the 180 to 390 mg/dm^3/hr attained in the yeasts tests.

Yeast production on wastewaters enriched with sucrose--

The introduction of sucrose has resulted in elongated biomass production time of 6.5 to 7 hr as shown in Table 19. Sucrose was not a suitable carbon source for C.robusta and C.tropicalis 8 as far as the biomass yield was concerned. The specific growth rates for the two species have reached a level of 0.083 h^{-1} for C.robusta and 0.052 h^{-1} for C.tropicalis 8, and then decreased gradually to zero as shown in Figure 61. The biomass increase was small and amounted to 1.56 g/dm^3 for C.robusta and 1.49 g/dm^3 for C.tropicalis 8.

The yeasts C.tropicalis 11 and C.utilis had multiplied according to a different pattern. The specific growth rate has reached, respectively, 0.189 and 0.206 h^{-1}, and then decreased to zero (Figure 61); while the productivity was 0.934 g/dm^3/hr and 1.26 g/dm^3/hr, respectively. The biomass increase was 7 g/dm^3 for G.tropicalis and 9.13 g/dm^3 C.utilis 3.

It was characteristic for all cultures that the biomass increase has gradually deteriorated to zero (Figure 61). Although the contents of nitrogen, phosphorus, and DO were sufficient, the yeasts had halted the uptake of sucrose. It seems that this phenomenon is the result of accumulation of inhibiting metabolites, a thing to be expected from periodic or semibatch cultures where the biomass and substrate are not exchanged.

Candida robusta has again proved to utilize the most of nitrogen (78 percent removal of N-NO_2^-), while removing other nutrients to the degree similar

TABLE 19. YEASTS PRODUCTION ON FILTERED PIGGERY WASTEWATERS WITH CARBON ENRICHMENT - REMOVAL EFFICIENCIES

	C.tropicalis 8 + sucrose		C.tropicalis 11 + sucrose		C.robusta + sucrose		C.utilis			
							+ sucrose		+ molasses	
	Raw	Removal	Raw	Removal	Raw	Removal	Raw	Removal	Raw	Removal
	mg/dm^3	%	mg/dm^3	%	mg/dm^3	%	mg/dm^3	%	mg/dm^3	%
COD	3,860	35	3,040	-	24	41	3,860	54	5,568	60
TKN	875	35	1,060	-	14	60	875	62	1,158	76
$N - NH_4^+$	400	25	370	-	542	27	400	74	643	84
$N - NO_2^-$	0.01	20	0.03	-	0.02	78	0.01	30	0.206	13
$N - NO_3^-$	5.0	increase 6	13	-	11	increase 15	5	increase 8	0.30	0
$P - PO_4^{-3}$	736	15	680	-	860	5	736	76	468	84
SOC	900	28	1,125	-	850	41	800	37	2,000	69

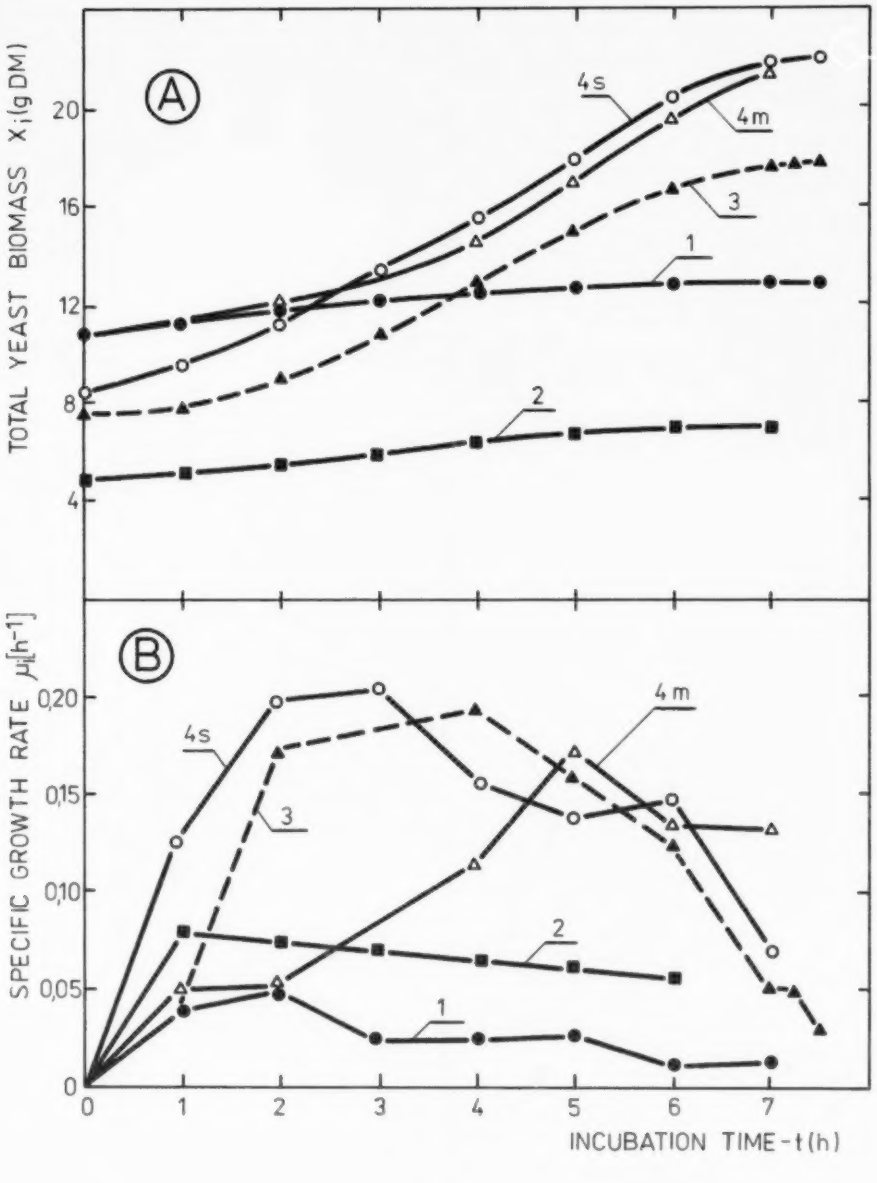


Figure 61. Semi-dynamic (batch-fed) fermentation: (A) Specific growth rate; (B) Biomass increase.

to tests without enrichment (Table 19). The level of nutrient utilization for C.utilis 3 has increased and the removals were 62.3 percent TKN, 74 percent $N\text{-}NH_4^+$, 30 percent $N\text{-}NO_2^-$, and 75.5 percent $P\text{-}PO_4^{-3}$. In spite of adding carbon the COD removal increased to 54.3 percent. Contrary to C.tropicalis 8 and C. robusta, this species showed good cell yield, similar to C.tropicalis 11.

The protein content in C.utilis 3, C.tropicalis 8, C.tropicalis 11, and C.robusta was, respectively, 429, 437, 476, and 434 mg/g. The aminoacids composition was similar to C.utilis from spent sulphite liquors, or C.utilis grown on molasses by Peppler (118). A somewhat lower content of leucine, isoleucine, treonine, methionine and cystine has been found for the C.utilis 3 and C.tropicalis 11. The digestible protein varied from 60 to 64 percent of the total protein.

It is interesting to compare the specific cell yields Y_s per g of nutrient removed for the enriched wastes (Table 20) with those for wastes without enrichment (Table 18), as well as respective SOC and COD removal rates. The Y values show excellent utilization of carbon (and nitrogen) by C.robusta and C.tropicalis as compared to poorer use of the nutrients by C.utilis. This is coincidental with the findings of the batch study preceding this work (117). The comparison of removal rates, calculated as in wastewater treatment operations, shows that enrichment provides for higher rates. It should be pointed out, however, that the increase is not large enough to offset the high cost of added sucrose, and that C.robusta and C.tropicalis are still excellent yeast species for piggery wastes.

Yeast growth on wastewaters enriched with molasses--

Only C.utilis 3 species were tested on beet molasses enriched wastes, which was found to be a better carbohydrate substrate than sucrose. The productivity was equal to 1.58 $g/dm^3/hr$ and was higher than that obtained with sucrose (1.26 $g/dm^3/hr$ - Table 20). Similarly, higher conversion of substrate components into cell biomass was found. The cell yield was equal to 115 g/mole as compared to the yield with sucrose (95 g/mole) and was higher throughout the test. A milder inhibiting rate was found during the test with molasses, the biomass increase was still quite intense after 7 hours, i.e. time of almost complete

TABLE 20. TESTS WITH CARBON ENRICHMENT - YEASTS YIELDS AND KINETIC DATA

			C.tropicalis 8	C.tropicalis 11	C.robusta	Candida utilis 3	
Parameter	Symbol	Units	+ sucrose	+ sucrose	+ sucrose	sucrose	molasses
Initial yeast quantity	X_o	g DM	10.79	7.54	4.71	8.40	10.8
Net biomass increase	Δx	g DM	2.24	10.51	2.34	13.7	11.05
Introduced carbon calculated as glucose	C	m mole	5.83	116.67	17.5	137.67	110.83
Duration of experiment	t	h	7	7.5	6	7.25	7
Maximum specific growth rate	μ_m	h^{-1}	0.05	0.19	0.08	0.21	0.17
Productivity	P	g DM/dm^3/h	0.21	0.93	0.26	1.26	1.58
Cell yield per nutrient used (removed)	Y	g DM/g nutrient					
Carbon		g DM/g C/h	0.3	-	0.22	0.19	0.16
Nitrogen		g DM/g N/h	0.7	-	0.30	2.28	1.19
Phosphorus		g DM/g P/h	2	-	6.5	2.28	2.67
COD		g DM/g O_2/h	0.09	-	0.13	0.04	0.04
Average removal rate coefficient	k(SOC)	10^{-3}dm^3/mg C/d	0.04	-	2	3	2.6
	k(COD)	10^{-3}dm^3/mg O_2/d	0.4	-	1.2	3	2.6

halt of activity in the sucrose system (Figure 61). The phenomenon of better yields with molasses may be explained by the presence of additional micronutrients in molasses that have a positive effect on yeasts.

The use of beet molasses instead of sucrose yielded the following increase of removals: TKN from 62 to 76 percent, $N\text{-}NH_4^+$ from 74 to 85 percent and $P\text{-}PO_4^{-3}$ from 76 to 84 percent (Table 20), in spite of the fact that molasses brought in an additional load of pollutions.

DISCUSSION AND CONCLUSIONS

The research has shown that various physicochemical methods of primary pig wastes treatment to increase the content of easily available carbon are not efficient technically and economically. It may also be shown that enrichment with molasses is economically unfeasible as the molasses is becoming an expensive and scarce component of animal feeds.

With the selected species of Candida yeasts, it is feasible to produce SCP for animal feeding purposes. It is, however, important to keep in mind the fact the full scale yeast production process may require continuous culture, sterile conditions which may not be feasible with piggery effluents. At the same time, the efficiency of wastewater treatment will not offset the high cost of yeast production, and the carbon that will be incorporated in yeast cells will originate primarily from added molasses.

In view of above the future work will have to go along the lines of finding mixed yeasts cultures with low carbon requirements as well as finding alternative low-cost waste carbon source in agriculture such as silage effluents or potato processing plant wastes.

Preliminary studies with four species of Hansenula yeasts: Hansenula canadensis (W), henricii (W), nonfermentans (W), Wickerhamii (W) obtained from Dr. A. Kockova-Kratochvilova catalog (Btatislava) have proved better adaptability to the pig wastes conditions. The Hansenula yeasts are capable of utilizing for metabolic purposes other forms of carbon than the easily biodegradable carbohydrates, e.g. fatty acids, alcohols, etc.

The conclusions of the work done on Candida yeasts may be summarized as follows:

1. The use of raw piggery wastes without carbon enrichment has yielded unsatisfactory effects both in case of biomass yield and wastewater treatment, although the unit utilization of CNP nutrients was quite high.
2. Sugar beet molasses was found the most appropriate source of easily available carbon.
3. The introduction of carbon results in significantly larger decrease of nitrogen and phosphorus compounds from piggery wastes.
4. When sucrose was used, the best yields and pollutant removals were found for C.utilis 3 and C.tropicalis 11 in dynamic tests.
5. The enrichment with molasses (C.utilis 3) yielded the following increases in removals, compared with the sucrose system: TKN from 31 to 76 percent; COD from 48 to 58 percent; PO_4^{-3} from 42 to 84 percent; and SOC from 64 to 69 percent.
6. The productivity of C.utilis 3 on molasses-enriched piggery wastes was increased, in comparison to the raw wastes system: 0.507 to 1.578 $kg/m^3/hr$ while the maximum specific growth rate from 0.125 h^{-1} to 0.172 h^{-1}.
7. The productivity of C.tropicalis 11 increased, after enriching with sucrose, from 0.327 to 0.934 $kg/m^3/hr$ and the maximum specific growth rate from 0.105 to 0.189 h^{-1}.
8. The metabolic by-products of yeast production result in the biomass growth inhibition. The effluent quality is still not satisfactory from the standpoint of the follow-up treatment.
9. The yeasts grown on piggery wastes have aminoacids composition similar to those grown on spent sulphite liquor and on molasses alone and evidence a lack of swine wastes odors.
10. The unit carbon utilization rates (g DM/g C removed/hr) are generally higher for wastes without enrichment; C.robusta has shown the best conversion rate in both the raw and enriched wastewaters.
11. The removal rate coefficients for systems without enrichment are equal to 0.001 (SOC) and 0.0006 to 0.0011 (COD) $dm^3/mg/d$ and are comparable to activated sludge systems working on presettled wastes

(K = 0.0004 dm^3/mg/d). The coefficients for enriched systems are higher due to the selective removal of more available carbon.

12. The protein content in the Candida species is 43 to 47 percent, the digestible protein content was 263 to 305 g protein/kg.TS. The amino acids content indicates excellent applicability of these yeasts as feed components certain methionine deficiency calls for supplementation.

SECTION 10

WASTEWATER PONDS FULL TREATMENT SYSTEMS

METHODS

A series of four ponds was studied in laboratory conditions in a setup as in Figure 62. The system consisted of an anaerobic pond followed by an aerated pond and two oxidation-stabilization ponds. The relative capacities are presented in Table 21 together with percent HRT in each pond.

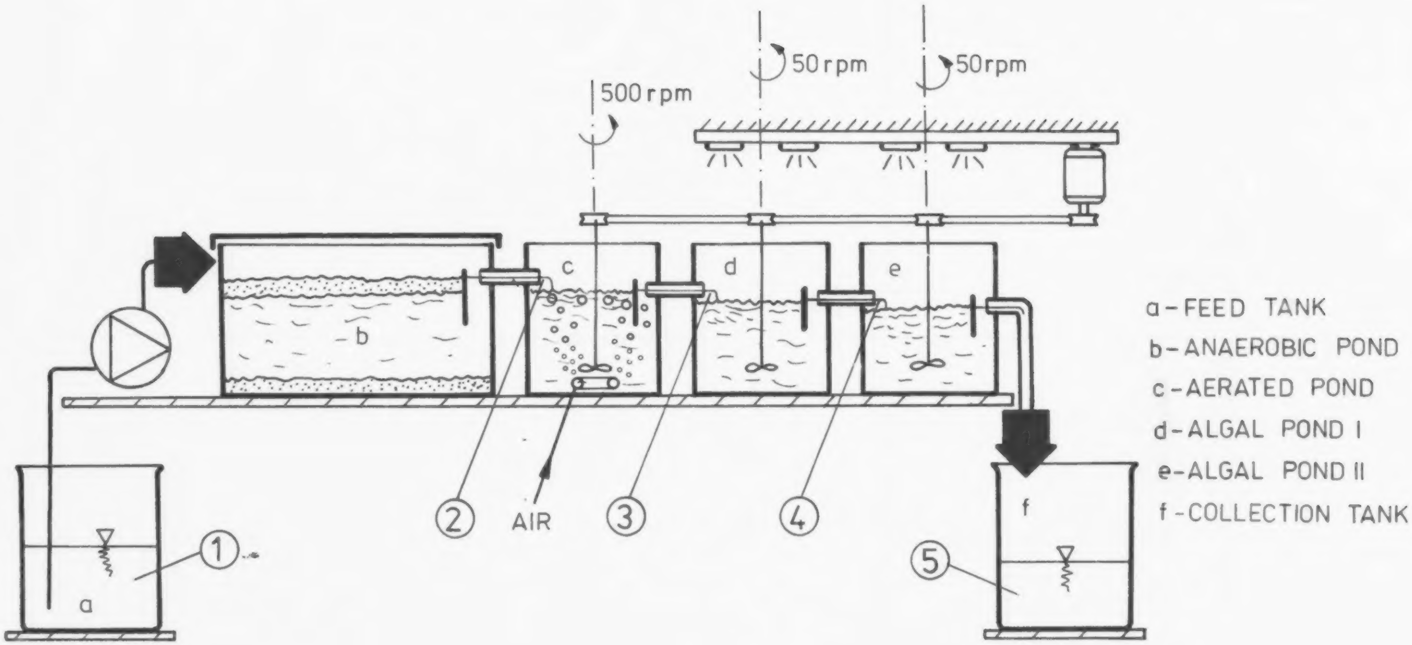
TABLE 21. WASTEWATER POND SYSTEM'S PARAMETERS

Pond	Area m^2	Volume dm^3	% HRT
Anaerobic	0.180	46.00	43.20
Aerated	0.090	21.75	20.42
Oxidation - 1	0.090	19.75	18.54
Oxidation - 2	0.090	19.00	17.84
TOTAL	0.45	106.50	100.00 %

The anaerobic pond was covered but was not air-tight, the aerated lagoon was both mixed and aerated. The oxidation ponds were continuously mixed to assure full utilization of their active volume.

The polishing (oxidation) ponds were lighted 12 hr/day. The seeding with algae, collected from natural pools contaminated with piggery wastes biological effluent, was done once throughout the experiment. Anaerobic pond was seeded several times with actively digesting anaerobic sludge.

The whole experiment lasted 16 months. Two parallel systems were investigated at one time. The steady state conditions were assumed after passing of time equal to 4 to 5 HRT. The whole system was closely investigated as a


500 rpm
50 rpm
50 rpm
b
c
d
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AIR
a
f
①
②
③
④
⑤
a-FEED TANK
b-ANAEROBIC POND
c-AERATED POND
d-ALGAL POND I
e-ALGAL POND II
f-COLLECTION TANK

Figure 62. Layout of the wastewater ponds system.

series of individual unit processes. The samples were collected in five locations as in Figure 62. Additionally, samples for TVS and TSS were collected from the anaerobic and aerated lagoon to evaluate the concentration of active biomass. The analyses performed routinely on the samples one thru five included: pH, DO, $BOD_{5,f}$, COD_{nf}, COD_f, TS, TVS, TSS, VSS, DS, TKN, $N\text{-}NH_3$, NO_2, NO_3, and N-org. Other parameters were determined sporadically. The following presentation is based on at least 6 systems, 10 runs, 5 samples and 16 analyses = 4800 individual data points.

RESULTS AND DISCUSSION

Due to space limitations, only the overall removal data for the whole treatment train will be presented in Table 22. Other results are presented graphically in Figures 63 and 64. It follows from the table and Figure 63 that the removal of soluble organics gains little after HRT = 60 days and that the stability of effluent quality improves at retention times HRT $\geq$ 30 days. Comparing this with data in Figure 64, which presents concentration of various forms of nitrogen versus HRT, one arrives at conclusion that basic carbon and TKN biodegradation is completed at HRT $\geq$ 30 days and that nitrification begins to take place beyond that retention.

The kinetics of biological processes in individual ponds and analysis of nitrogen pathways indicate several areas where full scale research should be directed. The problems of wastewater recycle to improve nitrogen removal, biomass harvesting and heat conservation are all considered as factors that could make the process more efficient.

TABLE 22. OVERALL EFFICIENCY OF WASTEWATER TREATMENT IN THE PONDS SYSTEM

		Hydraulic retention in all ponds days					
Parameter (g O_2/dm^3)		7	14	30	45	60	90
Influent (S_o)	COD_{nf}	14.07	14.07	13.82	14.00	13.82	14.00
	BOD_{nf}	5.51	5.51	5.44	5.51	5.44	5.51
Effluent (S_o)	COD_{nf}	1.46	0.91	0.45	0.35	0.29	0.20
	BOD_{nf}	0.75	0.43	0.22	0.17	0.14	0.11
Average temperature of the run (°C)		21.5	21.5	22.5	22.4	22.5	22.4

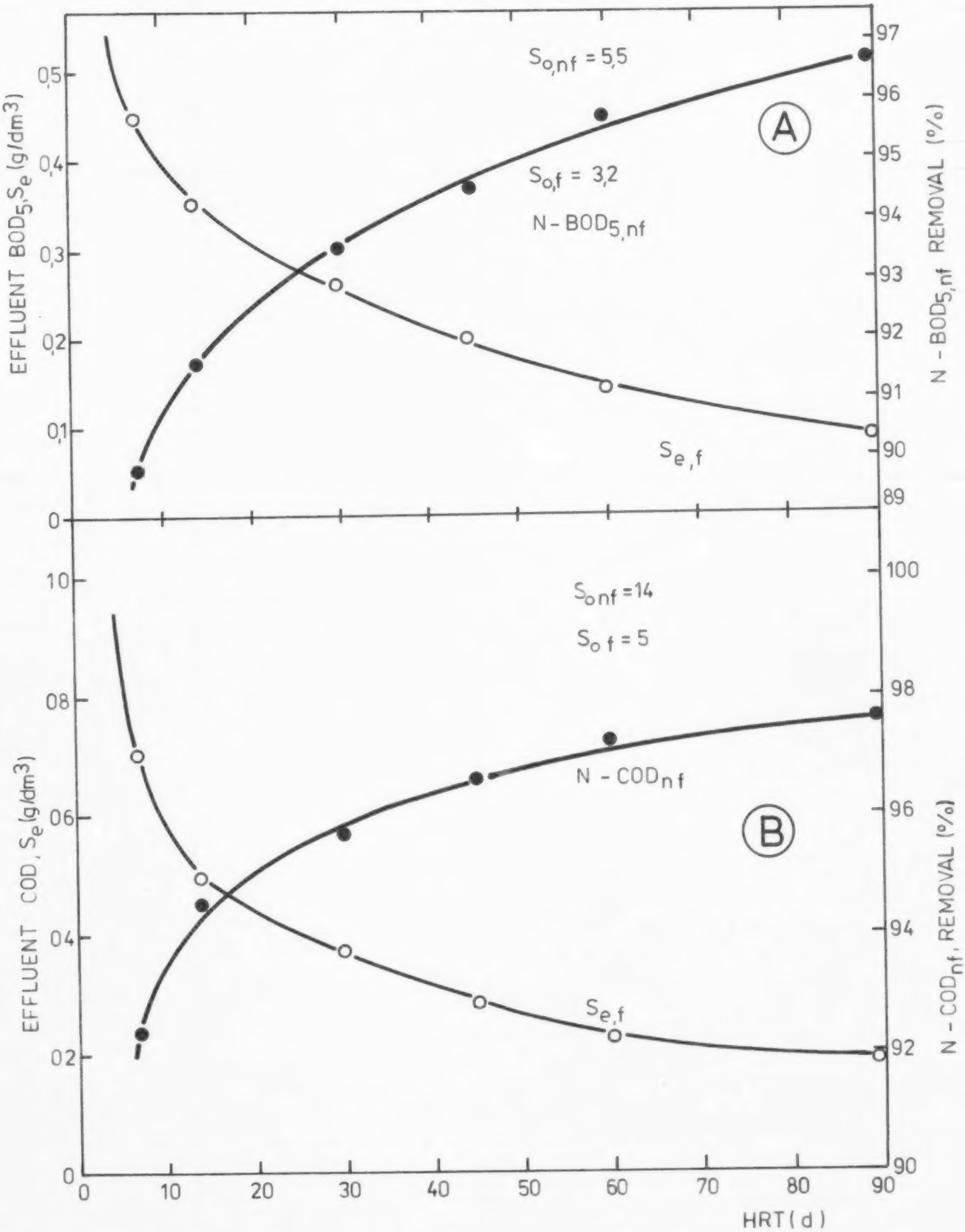


Figure 63. Effects of overall retention on organics removal in the ponds system.

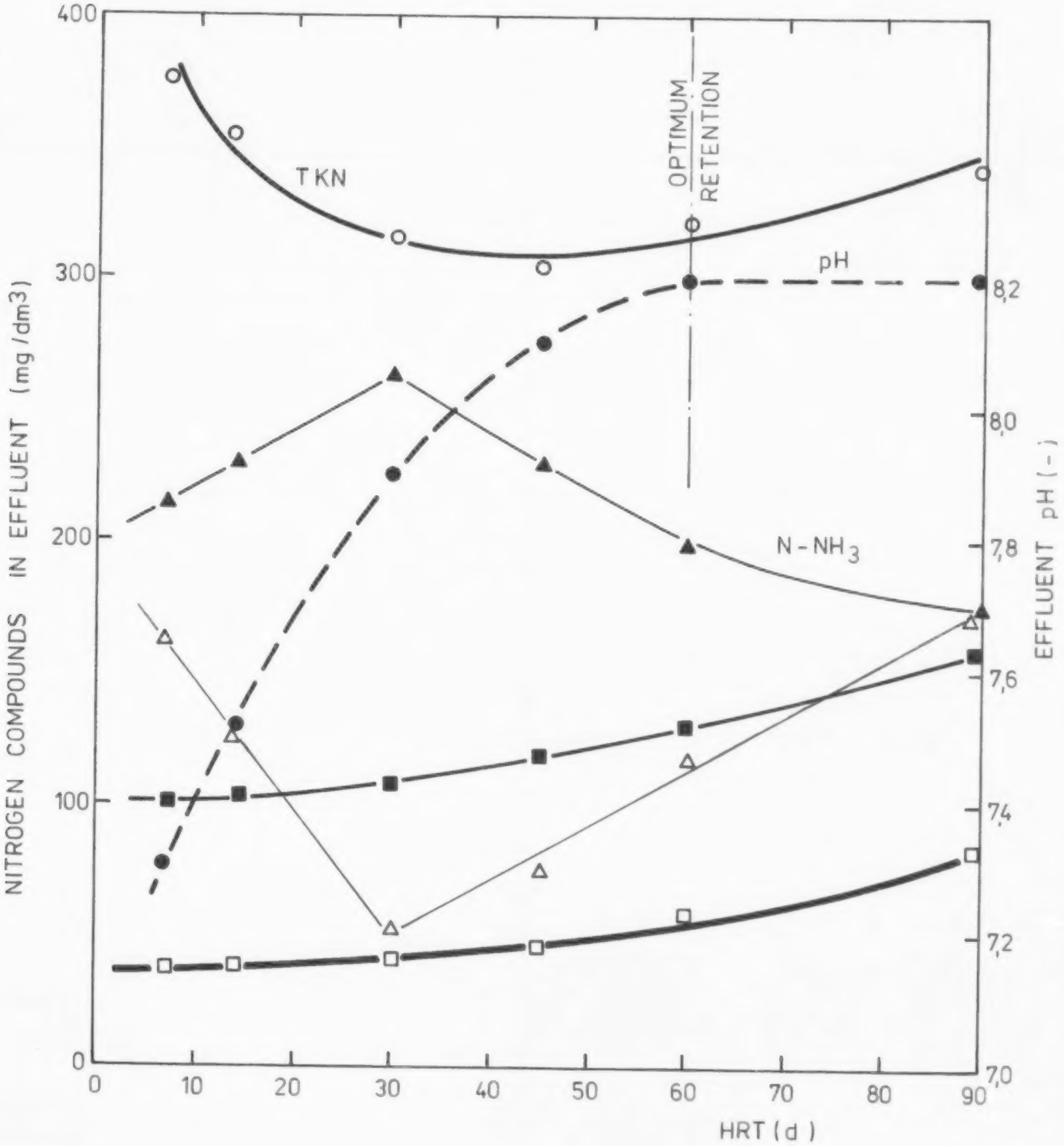


Figure 64. Nitrogen compounds and pH in the effluent from polishing pond II° versus overall retention in the system.

To summarize these findings, it is assumed that in full scale, a system with HRT = 60 days should yield 97 percent COD_{nf} and 97 percent $BOD_{5,nf}$ removal and an effluent COD_f and $BOD_{5,f}$, respectively, 250 and 150 mg O_2/dm^3 in summer conditions.

In order to improve the efficiency of the overall treatment system an additional polishing step is required, particularly to account for the winter conditions. Soil filtration with wastes introduced three feet underground, such as used at some rural treatment plants could be a natural solution, in line with the simple to operate, main waste treatment system.

SECTION 11

PROTEIN RECOVERY

INTRODUCTION

The protein deficit in the developed countries directly related to the deficit of animal feed. In Poland close to 85 percent of protein is used as animal feed and only 15 percent for direct consumption. The forecast for 1990 is 1.1 million tons for direct consumption and 7.7 million tons as animal feedstuff. The conversion of plant protein to animal protein involves significant costs and high losses which may amount to over 80 percent of the applied feed.

The increasing feed deficit in animal husbandry can be partly alleviated in conjunction with measures leading to improvement of the wastewater efficiencies. Two methods of utilization of the energetic potential of animal wastes are used: direct recovery and recycling of manure into feed and indirect method of conversion into microorganisms biomass, the SCP. The literature perusal reflects the increasing interests particularly in the second method (111, 122, 126, 127, and 128).

This section will discuss the feed values of screenings separated from piggery wastes, and of excess activated sludge, yeasts of the Candida type and of algae grown on treated effluents. Yields and effects will be presented and amino-acids content will be defined and compared with other feed components. Possible full scale application feasibility will be reviewed.

Methods

As noted by Martin et al. (137), animal manures can be divided into three general categories: 1) energy feedstuffs; 2) protein feedstuffs; and 3) forages. Energy feedstuffs, such as corn, contain less than 20 percent protein, less than 18 percent fiber and are high in easily available energy.

High protein feeds contain more than 20 percent protein. Forages consist of vegetative materials high in fiber, usually over 18 percent. Protein feeds have the highest monetary value, followed by energy feeds and then forages.

The following analysis will be based on protein and amino-acids determinations in recovered material. References to feeding trails reported by others will be made based on literature.

The estimate of total protein (TP) content was made on the basis of total Kjeldahl nitrogen analysis and calculation of TP = 6.25 TKN. The digestible protein (DP) content was based on the same TKN analysis made on material after 48 hours digestion with pepsin in presence of hydrochloric acid (129). The ratio of DP/TP is equal to digestibility index (DI). The amino-acids content was determined by means of an amino-acids analyzer.

DIRECT RECOVERY

Recycling of solids from piggery wastes has been practiced on experimental scale in several countries and is still not sanctioned by the Polish health authorities or the U.S. Food and Drug Administration. Several studies have shown negative effects, notably the one by Harmon (131) who noted weight loss in swine fed anaerobically predigested solids.

In one Polish study (132) 64 percent and 50 percent of dried piggery solids were added to the following respective feed components in two mixes: 22 percent and 34 percent of barley, 5 percent and 7 percent of beans, 4 percent of corn, molasses and additional minerals. In the first case the feed gave a yield of 865 g LW/day while the second feed, the yield was 1019 g LW/day of cattle. The studies of meat quality revealed no significant difference between the cattle fed rations with wastes and the controls.

In another study by Flachowski et al. (134) the piggery wastes screenings were preserved with urea and treated with sodium hydroxide and fed to bulls with other feedstuffs, with positive effects.

The work of Dzieniechowicz (150) on direct recycle of piggery waste screenings has demonstrated that both sheep and cattle can take up to 50 percent of dried solids in their diet. The feed containing 50 percent of screenings had 23 percent of protein, 4.23 percent fat, 18.71 percent of fiber and 33.37 percent nonnitrogeneous substances yielded a daily gain of 1326 g in beef cattle, without an apparent sign of health or meat quality deterioration.

It is noted that numerous studies on ensiling prove increasing applicability of the process to protein recycling (135, 136). Ensiling improves the digestibility of the waste material and increases the value of the by-product when incorporated in feedstuffs.

Table 23 illustrates the protein content of various materials obtained from Farm A effluent studied in this project.

The protein and amino-acids analyses of screenings have shown that they can serve as a volumetric feed (forage feed) ingredient for ruminants. The screenings contain 7 to 9 percent TP of 45 percent digestibility, large amounts of amino acids and 200 g/kg DM of mineral components. The low digestibility is the result of fiber content.

An interesting experiment is presently run by authors at Plant A. The screenings are placed in 20 to 40 cm layers on a sheet of plastic foil. The seeds of oats, rape and lupin are planted and the resulting forage, together with the base substrate undergoes ensiling or is fed to the drier. The procedure should allow for 3 to 4 crops/year provided they are covered in the winter time.

Direct recovery of solids, as screenings in the process of dynamic sieving (sieve 1 to 1.5 mm mesh) is practiced at large farms as a method of solids removal for disposal rather than a direct economic incentive. The low protein content places screening in the group of low cost forage feedstuffs. The economic comparison of costs of recovery with monetary value of solids (approximately 5 to 6 tons/day wet weight are recovered at Farm A) makes solids removal by screening an unnecessary treatment step. This is particularly true if settling tanks and/or anaerobic digestors are introduced.

TABLE 23. TOTAL AND DIGESTIBLE PROTEIN IN PIGGERY EFFLUENT WASTE MATERIALS

Material	Protein (mg/g DM)* Total	Digestible	Digestibility Index (%)
1. Solids from dynamic screens	84.2	37.0	45.8
2. Excess activated sludge	413.4 376.2	251.5 237.4	60.8 63.0
3. Mixed algal - bacterial cultures - Chlorella and Scenedesmus predominant	225.3 372.1 269.1	110.5 191.4 133.7	49.0 49.9 49.7
4. Yeasts monocultures:			
C.robusta 1	429.2	271.0	63.1
C.tropicalis 11	437.5	281.1	64.2
C.utilis 3	433.0	262.7	60.5
5. Lemma minor from the algal ponds (lab.)	274.6	216.0	78.7
6. Daphnia Magna** on pig manure diluted 1:1	500.0	-	-

*DM - dry matter
** - based on data by Jarocka (130)

Other efforts in direct recovery include separation of feces by hanging nets below slatted floors (133), but the economics of the process are still questionable.

In conclusion sieving to recover solids does not seem to be economically efficient. Recovery and processing through high temperature driers should be practiced at plants where dynamic screens are already installed, however, alternative methods such as composting and ensiling should be introduced.

CONVERSION INTO BACTERIAL SCP

Excess activated sludge may contain significant quantities of protein from 380 to 530 g/kg DM and beneficial quantities of vitamins and minerals. Several attempts on direct refeeding of activated sludge from under-floor-oxidation ditch back to swine were shown successful by Harmon (131).

In this country centrifuge concentration was tried in two cases to dewater excess sludge for recovery. In experiments in Kolbacz 22 percent DM (138) was attained with 24 percent raw protein in the dry mass. The excess sludge was from the 48 hr aeration tank operating at F/M = 0.5 kg O_2/kg MISS/d (BOD_5), in the Gi-Gi system shown in Figure 6. The centrifuge cake was used for preparing silage of the composition as in Table 24. The prepared silage had good taste and odor and was only 9 percent less digestible than the normal silage. The first silage contained protein 36 g/kg and 440 g DM/kg while the second, respectively, 40 g/kg and 430 g DM/kg.

In the authors' experiments (29) excess sludge from Plant A of the Vidus type was centrifuged in pilot scale in 5 m^3/hr installation of a decanting Humboldt-Vedag centrifuge. Various water quality grade coagulant aids were used to improve the dewaterability of excess activated sludge; some 13 percent of total solids (DM) were attained in the cake with some 39 percent of crude protein in the DM. The digestible protein was 237 to 251 g/kg with 61 to 63 percent DI. The material thus recovered was fed into an industrial dryer. Strong odors have precluded longer experiments, however, the final pelleted product had very good organoleptic properties. The amino-acids spectrum is presented in Table 25, against the values for chicken eggs.

In conclusion excess activated sludge is an excellent high protein feed, with high vitamins content and high digestibility. The present processes of piggery wastes treatment are based on activated sludge and thus recovery seems feasible. The major problem is the high cost of dewatering and drying. Presently, these costs make the process uneconomical.

TABLE 24. THE COMPOSITION OF SILLAGE PREPARED WITH EXCESS ACTIVATED SLUDGE

Components	% Weight	
	Silage I	Silage II
Corn grain	27	–
Barley grain	–	25
Hay cut	7	–
Straw cut	–	6
Grass silage	23	28
Activated sludge cake	43	41
TOTAL	100%	100%

TABLE 25. AMINO ACIDS COMPOSITION OF PROTEIN FROM RAW WASTES SCREENINGS, EXCESS ACTIVATED SLUDGE AND DUCKWEED

Amino Acids mg/g DM protein	Excess activated sludge		Solid Screenings		Duckweed Lemma Minor	Chicken Egg
	Run 1	Run 2	Run 1	Run 2		
1	2	3	4	5	6	7
Lysine	4.2	4.9	3.5	3.3	4.1	6.3
Histidine	2.0	2.0	1.6	1.5	1.9	2.1
Arginine	3.6	3.4	3.2	3.2	7.4	6.4
Asparg. Acid	7.1	6.6	5.2	5.3	14.2	-
Treonine	3.7	4.3	2.8	2.9	3.6	5.0
Serine	3.2	3.1	2.6	2.7	3.1	-
Glutamic Acid	7.6	8.2	7.9	8.4	8.5	-
Glycine	4.3	5.0	3.7	4.4	4.0	-
Alanine	6.2	7.7	4.1	4.5	5.1	-
Valine	4.6	5.6	3.7	3.8	4.3	7.1
Methionine	1.1	1.2	0.4	0.2	0.7	3.1
Isolwucine	3.4	3.9	2.7	2.6	3.4	6.8
Leucine	6.0	6.7	4.5	4.2	5.6	9.0
Tyrosine	2.5	2.9	2.1	1.8	2.9	4.4
Phenyloalanine	3.8	4.0	3.0	3.0	4.1	6.0
TOTAL	63.2	70.5	51.1	51.8	72.7	-
mg/g DM	261.1	265.1	43.0	37.4	199.5	-

CONVERSION INTO ALGAL PROTEIN

Numberous studies were conducted on the growth of algae on wastes, very few so far on piggery wastes. Most of the studies are on pure monocultures, but there are beginning to appear papers on mixed or symbiotic growth of algae and bacteria on wastes (140). In this project symbiotic continuous algal-bacterial cultures were grown in four laboratory ponds in series, 30 cm deep, illuminated 24 hr/day and kept at 22 ± 3^{o}C. Biologically treated piggery wastes were used, the effluent from Plant A final clarifiers.

Various species were tried, however, only Chlorella vulgaris and Scenedesmus survived the piggery wastes environment. The biomass was harvested by sieving, centrifuging and drying at 55°C. The average yields were presented in Section 7. The harvested biomass contained 22.5 to 37.2 percent of protein with DI = 49 percent and containing also 10 to 17 percent of raw cellulose and 3 to 8 percent fat.

Biomass harvesting and the problem of breaking the hardly digestible cell walls are presently the two major obstacles in fuller application of algal ponds (45, 141, 142). Comparison of sedimentation, filtration and centrifuging has proved the latter to be the preferred harvesting method although it is still far from satisfactory.

The cellulose and chemicellulose which makeup some 50 percent of the cell wall mass are only partly digested by ruminants. Thus, the final applicability of algae as feed can be evaluated only after a thorough disintegration of the cell wall and on samples that are free from bacteria.

The studies conducted in field scale by de Pauw (46) have yielded similar results. De Pauw attained yields of 1 to 10 g $DM/m^2/d$ at various temperatures in different seasons and has managed to grow on raw and pretreated piggery wastes, Scenedesmus, Chlorella v. and Coelastrum probascid. Other researchers, Müntz (143) and Goldman (43), have also found cell was digestibility to be the major obstacle. The future of algae application lies in solving the two problems: separation and digestibility.

Based on present difficulties, the solution is to use the algal ponds in natural ecosystems of aquaculture and using the developed biomass for fish production. Other methods to be evaluated include the use of algae as supplement to biogas generation such as pilot work in Italy by Micheli (72) and the development of mutants with low-cellulose-walls or larger volume to cell wall-surface-area ratio.

CONVERSION INTO YEAST PROTEIN

The production of protein by yeast is over two hundred times faster than in the conventional agriculture supplying the farms, and the studies show that higher protein contents are attained in yeasts than in field crops.

The fermentation yields in this project are described in Section 9. In the raw wastes fermentation the specific growth rate, productivity and the level of C, N, and P nutrients utilization were unsatisfactory. Much higher yeast production was attained on enriched wastes, however, then the cost was comparable to yeast production from molasses alone. The yeasts contain 43 to 47 percent crude protein of 60 to 64 percent DI. The results indicate the technological feasibility of protein recovery through yeast fermentation.

The high costs of yeasts fermentation due to the use of expensive and not readily available molasses suggest the use of integrated treatment-recovery systems. The combined system of feed yeast production, animal husbandry, and a joint water, wastewater management and treatment systems will allow the decrease of the overall costs.

It should be pointed out that a lot needs to be done to increase the overall efficiency of the process. In particular mixed yeast cultures should be considered, the mastering of the principle of continuous fermentation, and the decrease of costs of additional carbon.

Preliminary trials have verified the possibility of applying the continuous process. The maintenance of the steady state for prolonged periods of time without the need for inocculum and culture replacement is of major importance to process cost decrease.

It seems that before the solutions to these problems are found, yeast protein from piggery wastes will be economically unfeasible until further protein price increases occur.

NUTRITIONAL VALUE OF RECOVERED PROTEIN

Although the feeding trials are the best method of evaluating the nutritional potential, the chemical methods give rapid answers and usually are highly correlated with the biological tests.

Evaluation of the protein quality was made on the basis of analysis of 15 AA and comparing them to the whole egg protein, looking for the most deficient

AA as proposed by Ruszczyc (151). It is assumed that the deficient AA decides about the value of protein. Calculating in this manner the nutritional value of the recovered protein we have obtained: activated sludge 38 percent, yeasts 31 percent, algae 29 percent, Lemma minor 24 percent, and screenings 10 percent.

In all cases methionine is the limiting acid, however, it is an inexpensive commercially available component. Although thyrosine, valine and lisine are present at lower concentrations, the recovered SCP does contain the full spectrum of exogennic AA and as such is considered adequate feedstuff.

It should be noted that several sources suggest the use of Food and Agriculture Organization (FAO-UNO) reference protein standard which is given in Table 26. When comparing the AA content from Tables 25 and 27 with FAO standard, the nutritional values of recovered proteins are much higher as shown in Table 28. This and the fact that species grown on pure cultures, without inhibitors also reveal significant deficiencies, while at the same time they are considered fully acceptable, lead to the conclusion that the materials recovered from piggery wastes processing are adequate feedstuff supplements or substitutes.

All recovered protein may be used only as feed supplement, up to a maximum of 50 percent, due to low digestibility. Activated sludge, yeasts and Lemma Minor (duckweed) have proved to be the most easily digestible source of SCP; cellulollytic material was responsible for low digestibility of other SCP sources, particularly in case of algae.

The AA of algae is 162 to 145 mg/g DM, activated sludge 265 mg/g DM and yeasts 246 to 291 mg/g DM. When calculating these amounts in terms of mass per 100 g of protein, the AA content is 64 to 74 g for algae, yeast and activated sludge and some 50 g for solid screenings.

The possibility of using yeasts and algae has been demonstrated experimentally (147): yeasts can be used in feed up to 20 percent by fattening swine, up to 15 percent by small piglets and 10 percent by sows and boars. In feeding poultry, layers, and cocks one can use up to 20 percent of SCP yeasts.

TABLE 26. AMINO-ACIDS CONTENT IN PROTEIN RECOVERED FROM SYMBIOTIC ALGAL - BACTERIAL BIOMASS

Values in mg/g DM Protein	Algae				Reference	
	Mixed cultures - Plant A			Pure Cultures		
	I	II	III	Chlorella	Scenedesmus	FAO
Lisine	3.9	3.5	4.9	8.0	5.7	4.2
Histidine	1.8	1.7	1.6	-	-	-
Arginine	3.9	4.1	3.4	-	-	-
Asparg. Acid	7.5	3.2	7.2	-	-	-
Threonine	4.1	4.0	3.7	5.3	5.2	2.4
Serine	3.5	3.3	3.4	-	-	-
Glutamic Acid	8.2	7.9	8.1	-	-	-
Glycine	4.9	7.9	4.1	-	-	-
Alanine	6.7	6.8	5.5	-	-	-
Valine	4.9	4.8	3.9	6.2	7.2	4.2
Methionine	0.8	0.9	0.9	1.8	1.4	2.2
Isoleucine	3.8	3.6	3.0	4.8	4.4	4.2
Leucine	6.5	6.7	5.8	9.3	9.3	4.8
Tyrosine	3.1	3.0	2.4	-	-	4.8
Phenylalanine	3.9	3.9	3.7	6.6	4.6	2.8
SUM	67.6	65.9	61.4	-	-	-
Total mg/g DM	152.3	245.0	165.2	-	-	-

NOTE: Data from continuous culture four bacterial-algal ponds in series, treating biological effluent from Plant A.
Reference data on pure culture are from Boersma et al. (47).

TABLE 27. AMINO-ACIDS CONTENT IN PROTEIN RECOVERED FROM YEASTS GROWN ON FILTERED RAW PIGGERY WASTES ENRICHED WITH SUCROSE

Amino-acids mg/g DM Protein	Yeasts monocultures of Candida kind				Reference	
	C.robusta	C.tropicalis 11	C.tropicalis 8	C.utilis 3	Sulfite Liquor	Molasses
Lisine	4.9	5.5	5.5	5.1	6.7	10.7
Histidine	3.2	2.2	1.8	1.8	1.9	2.8
Arginine	3.0	3.4	2.8	2.7	5.4	4.7
Asparg. Acid	7.1	6.8	8.1	10.8	-	-
Treonine	3.8	4.3	4.0	3.8	5.5	4.8
Serine	3.3	3.9	3.4	3.1	-	-
Glutamic Acid	6.8	9.8	9.2	5.3	-	-
Glycine	2.8	3.7	3.1	2.4	-	-
Alanine	4.7	4.9	4.5	4.2	-	-
Valine	4.1	3.9	3.8	2.3	6.3	5.7
Methionine	1.0	0.9	0.9	1.0	1.2	1.4
Isoleucine	3.9	4.0	3.5	2.9	5.3	7.3
Leucine	4.7	5.3	5.0	4.2	7.0	8.1
Tyrosine	2.6	2.5	2.6	2.1	3.3	1.4
Phenylalanine	2.9	4.2	3.0	2.4	4.3	4.1
TOTAL	62.9	65.3	61.3	58.9	-	-
mg/g DM	269.7	285.4	291.2	246.7	-	-

NOTE: Reference data is for pure Candida utilis grown on spent sulfite liquor and molasses (Peppler, 144).

The experiments have documented the beneficial role of the vitamins, minerals and carbohydrates in algae, which when fed to swine (Chlorella) up to 25 percent in the diet resulted in better weight gains (149).

TABLE 28. NUTRITIONAL VALUE OF PROTEINS BASED ON METHIONINE DEFICIENCY

Protein From	Against Whole Egg (%)	Against FAO Standard (%)
1. Screenings	7-13	9-18
2. Activated sludge	35-39	50-55
3. Algal-bacterial biomass	26-29	36-41
4. Pure algae: Chlorella	58	82
5. Scenedesmus	45	64
6. Yeasts (this study)	29-32	41-45
7. Yeasts: sulfite liquor	39	54
molasses	45	64
8. Lemma minor	23	32

DISCUSSION AND CONCLUSIONS

In ideal conditions 1000 kg LW of beef cattle produces 1 kg/day of protein, 1000 kg soybean yield 100 kg/day, 1000 kg yeasts (DM) yield 100,000 kg/day and 1000 kg of bacteria may yield daily 100,000,000,000 kg of protein/day (148). This short comparison although biased, since the wastewater based crop is collected on year-around basis, as a whole plant with "roots," etc. as opposed to land based yields, demonstrates the nutritional potential of SCP as the substitute of other relatively inefficient agricultural products.

The SCP is synthesized in numerous countries from petroleum derived hydrocarbons. Contrary to such sources, where the danger of introducing carcinogens is quite apparent, the use of agricultural by-products for SCP synthesis has to receive a much wider attention. The energetic potential of animal wastes is 30 percent of the input feedstuff, sometimes in an unchanged form.

Numerous problems need to be solved before wider application of recycle and SCP conversion will be practiced. It has already been demonstrated, for instance that anaerobically digested dried pig wastes sludge yields definitely negative effects when fed to swine.

As a rule, higher benefits are attained when recovered protein is fed to another group of animals, as for example with dried poultry waste (DPW) fed to cattle, or swine solids fed to cows and sheep.

The conclusions may be itemized as follows:

1. There are potential possibilities of direct recovery of protein in waste solids from pig wastes. Complex animal hygienic studies are, however, needed before full application, since the present experience is short-termed and narrow in scope although very encouraging. The sterilization and/or drying is not the best method of screenings preparation due to cost and odor problems. The desired alternative is ensiling with other feedstuffs. The direct recycle should be in open cycles, i.e. fed to animals of other kinds.
2. Based on protein content and digestibility analyses, the materials recovered from piggery wastes can be classified as: proteinaceous feedstuffs; excess activated sludge yeasts and Lemma minor; forage feedstuffs; raw waste solids and algae.
3. The following determinations on the recovered material were made: protein content (g protein/kg DM); screenings 34 to 37, activated sludge 240 to 250, algal-bacterial biomass 110 to 192, yeasts 263 to 281, L.minor 216; with respective digestibility indices 45 percent, 62 percent, 50 percent, 63 percent, and 78.8 percent; nutritional value compared to full egg AA content; screenings 10 percent, L.minor 24 percent, algae and bacteria 29 percent, yeasts 29 to 32 percent, and a.sludge 38 percent.
4. Based on analysis of AA content in the FAO reference protein and in the SCP recovered from other substrates, it is concluded that although the material recovered in this study have generally lower AA content, they can be used as adequate feedstuff components.

5. Algae SCP grown on piggery wastes are an excellent food source with high protein, vitamin and minerals content. The research should in the future solve the problem of low digestibility of cell walls and the difficulties in harvesting. At present the immediate application would be in closing the cycle through aquaculture, fish cultivation, as other methods are too expensive and not simple enough for the rural environment.

6. Yeasts grown on piggery wastes have quality similar to the commercial product. There are no additional cost benefits when the pig wastes are used as substrate since large quantities of costly beet molasses need to be added, while the danger of contamination of the culture is much more eminent.

   The possible more economical alternatives are: integration of waste treatment and recovery systems of regular yeast manufacturing plant and pig farm; and the use of mixed yeast cultures and the use of yeast with low carbohydrate requirements; and the use of other inexpensive waste carbohydrate sources.

7. The most promising techniques of piggery wastes utilization involve combined waste treatment and direct as well as SCP protein recovery and industrial complexes that attempt at closing the nutrient and food cycles: nutrients, SCP, aquatic animals, feed, and farm animals.

8. Excess activated sludge is found to be of the highest value as feedstuff, however, as the SCP source, it is of minor importance since the activated sludge is becoming uneconomical for piggery wastewaters and will have to be replaced in the future by low-energy-consumption treatment systems.

SECTION 12

EVALUATION OF VARIOUS WASTE TREATMENT AND RECOVERY SYSTEMS

OUTLINE OF THE ECONOMIC ANALYSIS

Economic optimization of waste treatment, recovery systems is a complex process, which if to be done correctly, requires sophisticated mathematical modelling and computer simulation of unit processes performance within the treatment train. It is observed, however, that the effects of the sophisticated approaches which include presumably all of the foreseeable variables may not be representative, frequently due to an inadequate data base assumption. In case of animal wastes the researchers are not consistent as to the actual price of biogas and recovered protein, the costs of comparable unit processes, etc.

Due to variations in the technological and constructional know-how of treatment facilities, it is not possible to apply literature data to processes derived in this work. For example, Genung et al. (51) calculates power use for three plants (design flow 3780 m^3/d): activated sludge (AS), trickling filter (TF) and anaerobic biofilter (AB), respectively as 963, 623, and 105 kWh/day with sludge handling included. It occurs to the author of this report that: a) removal efficiencies of each treatment train in this comparison are different, and b) the power input for the AS is 1.5 times the power input for TF and over 9 times that of an AB. In another paper Mills and Tchobanoglous (162) quote, for two plants ($Q = 4250\ m^3/d$) with AS and TF both featuring anaerobic digestion of sludge, the respective power use of 2671 kWh/day for an activated sludge plant and 723 kWh/day for trickling filter treatment train, where as the AS system requires 3.7 times more power than the TF system. The latter does not compare well with the 1.5 times factor quoted by Genung et al.

Similar large discrepancies are evident in the literature concerning strictly animal wastes treatment economics. For example, there is little agreement between various sources on such items in the economic analysis as: the power level for mixing the anaerobic digester, quantity of recoverable and recovered energy, unit costs of gas production, and removal efficiencies (69, 91, 160, 162).

Another conclusion from the perusal of literature on recovery from animal wastes is that economic conditions are so much different in various countries that the comparison yields contrasting results. Mills (161) comparing an aerobic and an anaerobic system for swine wastes has concluded that for Scotish farms above 100 head capacity the anaerobic treatment for biogas recovery is becoming economical. On the other hand, Hashimoto and Chen (91, 93) show that anaerobic digestion (AD) for cattle wastes become feasible economically above several thousand head capacity, U.S. conditions. Other authors show: the feasibility of anaerobic digestion for piggery farms of 24,000 + head capacity at natural gas costs of $\$2/10^9$J; and lack of economic justification for gas recovery at gas costs of $\$0.8/10^9$J, for farms as large as 240,000 head capacity (83).

The selection of the type of anaerobic digestion system is also not agreed upon by writers: some favor the thermophillic process, others indicate that there is more energy recovered from the long-term mesophyllic digestion.

Some writers use 10 to 14 days retention in a mesophyllic digestor, while others base their calculations on 20-day retention. This is an additional source of differences since the increased detention time results in more efficient unit gas recovery, however, the overall economy may deteriorate particularly in the flow-through digestors due to an increase in volume.

Summing this brief literature perusal: it is impossible to gain any knowledge of the true economic efficiency of the anaerobic digestion as a waste treatment method, with an additional gas recovery bonus, based on literature data. Similar situations exist in literature on economics of SCP recovery as noted in the chapter on protein recovery.

It was then decided that a special economic analysis will have to be made in this case of dilute piggery wastes from a typical industrial piggery farm.

Basic Assumptions

Almost all economic data reported on animal wastes deals with very concentrated or even semi-solid manures. In this project diluted piggery wastewaters will be evaluated from the standpoint of economic efficiency of their treatment for stream disposal. As opposed to the literature data where efficiencies of individual anaerobic digestors and their gas production are compared, full treatment trains will be evaluated with associated sludge handling facilities. Uniform standards for effluent quality and final sludge characteristics will be assumed for all compared systems. In this project the profit from recovery has a secondary meaning; the primary objective being: the decrease of the overall operation and maintenance costs, cutting down on imported materials (fuel oil and chemicals) and obtaining low quantity of well stabilized sludge, and acceptable year-around quality of treated effluent.

It is usually assumed that agricultural utilization of effluents, raw or pretreated, is always the preferred disposal method, since it results in the least harm to the environment and yields direct benefits. Jewell and Loehr (159) show that the nitrogen value of manures is \$0.013/hog/d while the energy potential of piggery manure is only \$0.0068/hog/d, which is two times less. The net benefit is still smaller when the difficulties in recovering the energy contained in significantly diluted wastes are compared with the relative ease of nitrogen application to crops. The conditions at numerous large farms make agricultural utilization impossible, and hence, this analysis deals with full treatment before stream disposal of wastewaters from two types of farms. One is a conventional farm of typical Agrokomplex technology, called Farm A, with the basic wastewater generation of 28 dm^3/hog/d and 10,500 head capacity. The other is a similar farm with a modified wastewater system, flushing of sewers with treated wastes and wastewater generation of 20 dm^3/hog/d with 15,000 head capacity called Farm B.

It has been shown so far that the presently used methods of piggery wastes treatment are inadequate because of low efficiencies attained, high process instability, resulting effluent variability, and mounting operational costs. It has also been documented that AD should be the basic biological preparatory process that alleviates several of these problems, yielding an effluent very well fit for further aerobic treatment. It is also fit for land disposal as shown in our studies, the effluent retains 90 percent N and P. Thus, the processes selected for comparison feature AD as a method of either sludge stabilization or wastewater treatment or both. Eight basic processes shown in Figures 65 through 70 were selected.

The diagrams depict only the unit operations that are included in the economic analysis. As a reference, a basic Vidus treatment system VIII (Figure 5 and 70) costs are used, calculated similarly as other systems based on current 1980 prices.

Wastewater loads and removal efficiencies--

Hypothetical Farms A and B are characterized by flows $Q_A = 300\ m^3/d = Q_B$; $L_A(COD) = 4200\ kg\ O_2/d$, $L_B = 6000\ kg\ O_2/d$; $L_A\ (TS) = 3013\ kg/d$, $L_B = 4305\ kg/d$: $L_A(BOD_5) = 1430\ kg\ O_2/d$, and $L_B(BOD_5) = 2040\ kg\ O_2/day$.

The removal efficiencies are based on our experimental data and are expressed only by means of COD and BOD_5. Influent to effluent concentration (mg O_2/dm^3 nonfiltered) ratios are: COD_A - 14,000/200 and COD_B - 20,000/200; $BOD_{5,A}$ - 4,770/45 and $BOD_{5,B}$ - 6,800/45. The effluent qualities assumed in this analysis were attained in the course of this study.

Conversion efficiencies and unit costs--

Efficiency of gas/electric power conversion is combined with the efficiency of the biogas fueled internal combustion engine and with the synchronous generator. Neyeloff and Gunkel (164) show the respective efficiencies as 16 percent and 90.0 percent which yield a product of 14.5 percent. Hashimoto and Chen (91) suggest an engine-generator efficiency of 38 percent as a maximum at 100 percent methane content, which for 60 percent CH_4 mixture yields overall efficiency of 23 percent. Recent work of Michelli (72) contains the most reliable data from full scale operation of the TOTEM (Total Energy Module) units at S.Agreste Farm at Todi, Italy, where 8600 pigs and 45,000 chickens are raised and effluent undergoes combined anaerobic treatment. The TOTEM is based on Fiat 127 engine and has the efficiency of 25 percent gas/power conversion and additional recovery of heat from the engine cooling water some 64 percent of the input energy. The writers have visited the operation at Todi and found that it yields enough energy to power and heat the treatment plant while the excess is utilized in the farms production sector. The anaerobic digester effluent undergoes anaerobic lagooning and aeration in an aerobic lagoon before being recycled to the farm.

In this analysis the 25 percent gas/power and 64 percent gas/heat conversion ratios are assumed. The gas calorific value is assumed 23.45 MJ/m^3 (M = 10^6), i.e. 5600 Kcal/m^3. The unit energy costs are given in Table 29. The conversion for electric energy is assumed based on TOTEM experience as 3384 Kcal/kWh.

It should be noted that 0.50 zl/kWh is an average for 1978-1979, the 1980 lowest present price is 0.66 zl/kWh for city users and 1.50 zl/kWh for individual use for heating during peak hours. However, two values will be used, 0.50 and 1.50 zl/kWh. The costs in dollars and energy densities in Table 29 are after Martin and Loehr (163). The analysis will be appropriate to the Polish conditions, as the prices of certain commodities, such as fertilizers, electricity, gas or coal on domestic market are set rigidly and are usually low when compared to other goods or to the fluctuating prices in the world market.

Based on these figures, the following recovery calculations can be made. Energy recovery may be effected through: 1) direct sale of gas, then the price of 1.20 zl/m^3 could be assumed; 2) conversion to power, then one obtains (5600 Kcal/m^3 0.25 percent efficiency)/(860 Kcal/kWh = 1.63 kWh/m^3), i.e. 0.81 to 2.44 zl/m^3 and an additional 60 percent recovery of heat yields 3360 Kcal/m^3, which at 232 zl/Gcal is equivalent to an additional 0.78 zl/m^3; and 3) direct use as heat in the plant, which at 70 percent efficiency of the gas fired boiler yields 3920 Kcal/m^3 or 0.90 zl/m^3, at city heat prices. In a remote location of the piggery farm the above underestimates the actual revenues from gas recovery.

TABLE 29. UNIT ENERGY COSTS

Energy Source	Energy Density	Unit Costs $ USA	 Zloties Poland	Notes
Gasoline (regular)	35.6 MJ/dm^3	0.283/dm^3	16 zl/dm^3	78 octane
Fuel oil	40.1 MJ/dm^3	0.268/dm^3	14 zl/dm^3	
Liquif. petroleum gas	25.5 MJ/dm^3	0.171/dm^3	1.18 zl/m^3	Mixture of natural and coal gas
Coal (anthracite)	30.0 MJ/kg	0.083/kg	0.55 zl/kg	
Natural gas	36.3 MJ/m^3	0.133/m^3	1.14 zl/m^3	Industrial consumer may pay up to 2.40 zl/m^3
Electricity	3.60 MJ/kWh	0.0434/kWh	0.5 to 1.5 zl/kWh	
City heat (coal fired plants)	-	-	232 zl/Gcal	Valid for a large city
Nitrogen (fertilizer)	-	0.013/hog/d	10.4 zl/kgN	
Phosphorus (fertilizer)	-	n.a.	8.5 zl/kg P	

NOTE: The prices quoted are sale prices based on 1980 averages. 1 U.S. $ is equivalent to 20 zl.

Methods of analysis--

Equation 6 from Section 4 will be used here. The method assumes approximately 10 years period of amortization of the capital investment. The costs and economic efficiencies of COD removal and of volume of flow removal (E_{COD} and E_Q) are based on current 1980 data. The data in Table 3 are calculated based on surveys of full scale plants erected between 1973 and 1976, thus, the numbers cannot be directly compared with the results of this economic analysis.

The recovery of biogas will be taken into account by subtracting from the maintenance and operation costs. When applicable, nitrogen and phosphorus costs will be substrated. The value of recovered protein is not taken into account, which is consistent with the findings of this study.

COMPARISON OF VARIOUS SYSTEMS

The resulting economic efficiencies expressed in zl/kg COD_{nf} removed and in zl/m^3 of wastewater treated are compiled in Table 32. The two variants A-10,500 and B-15,000 head capacity, of one treatment system are calculated at two power costs levels: 1 to 0.50 zl/kWh and 232 zl/Gcal; 2 to 1.50 zl/kWh and 500 zl/Gcal. In order to save space only two examples of calculations are given below and shown in Tables 30 and 31.

The costs of land is excluded from these considerations:

System I

The system (Figure 65) is based on studies presented in Section 10. The lagoon system shall yield, in favorable conditions, effluent COD_{nf} = 380 mg/dm^3 and $BOD_{5,nf}$ = 235 mg/dm^3. It is designed based on the following loadings: anaerobic lagoon 0.5 kg COD_{nf}/m^3/day, aerated lagoon 0.4 kg COD_{nf}/m^3/day, oxidation ponds 0.08 kg COD_{nf}/m^3/day. For variant A (10.5 thousand head), these loads yield respectively 30 days, 10 days, and 20 days HRT. To arrive at the design effluent COD_{nf} and $BOD_{5,nf}$ of respectively 200 and 45 mg O_2/dm^3,

---

1 cal = energy to heat 1 g water by 1°C; 1 cal = 4.1868 J.
10^6 Btu = 10^9 J = 10^3 MJ = 1 GJ. 860 Kcal ≅ 1 kWh (2850 J)

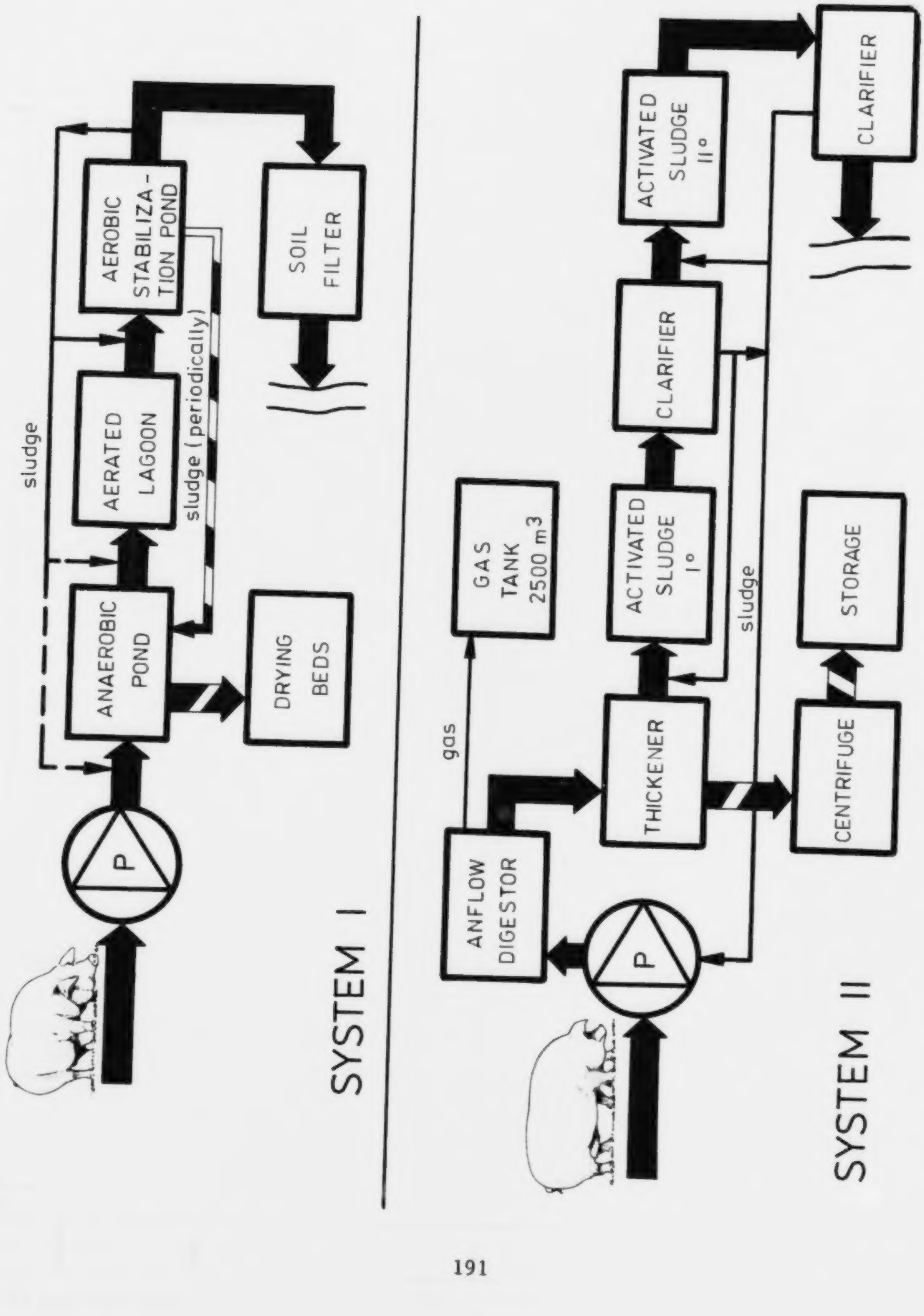

SYSTEM I
P
ANAEROBIC POND
AERATED LAGOON
AEROBIC STABILIZATION POND
sludge
sludge (periodically)
SOIL FILTER
DRYING BEDS
SYSTEM II
P
ANFLOW DIGESTOR
gas
GAS TANK 2500 m3
THICKENER
ACTIVATED SLUDGE I°
CLARIFIER
ACTIVATED SLUDGE II°
CLARIFIER
sludge
CENTRIFUGE
STORAGE

Figure 65. Layout of System I and II.

soil filters are designed as a polishing treatment step. These should have an area of 10,000 m^2 (1 ha) and will yield, based on full scale data from Plant D, Section 4, an effluent quality better than the design values on a year-around basis. Sludge treatment will include storage in the anaerobic lagoon and dewatering in the drying beds of 5000 m^2 area. The layout is consistent with the now prevailing concept of rural treatment plants consisting of earthen basins and simple structures that can be built by local agricultural enterprises and that are the easiest to operate. It should be noted, however, that the costs here are already high (Table 32) without even accounting for the costs of land required by this low-efficiency system.

System II

This system (Figure 65) features an ANFLOW reactor with 10 d HRT followed by a thickener (HRT = 1 d) and two-stage activated sludge tanks. The thickener reduces the volume of sludge to be dewaterd by centrifuge and allows for sludge recycle to ANFLOW in case of upsets and during the initiation of the anaerobic process. The activated sludge process is designed at HRT = 3 d, Farm A, and HRT = 6 d, Farm B, overall retention, with intermediate settling tanks. Staging of the process and constant temperature T = 20 to 25°C allow to attain steady effluent quality exceeding the design standards, temperature correction factor 1.053, $K_{20} = 6.6\ d^{-1}$.

Capital costs--

In order to illustrate the calculation procedures, capital costs for System II are presented in Table 30.

Further exemplary calculations for System II are performed for variant A-1; the results for System II: A-2, B-1, and B-2 are given in Table 32. With the excess activated sludge that undergoes gasification with raw wastes, the value of $SGP_o = 0.43\ m^3/kg\ COD_{nf}$ (in) and the calorific value of gas = 5600 $Kcal/m^3$ are conservative assumptions.

Energy balance--

Electrical energy recovered is:

$$EE_r = 0.43\ \frac{m^3}{kg} \times 4200\ \frac{kg}{d} \times 5600\ \frac{Kcal}{m^3} \times \frac{1}{3384}\ \frac{kWh}{Kcal} \cong 2980\ kWh/d$$

Heat energy recovered from the TOTEM engines:

$$HE = 1800 \frac{m^3}{d} X 5600 \frac{Kcal}{m^3} X 0.64 = 6.5 \text{ Gcal/d} = 2372.5 \text{ Gcal/yr}$$

The gross profit from recovered energy:

$$PE = 2980 \frac{kWh}{d} X 0.5 \frac{zl}{kWh} X 365 \frac{d}{yr} + 2372.5 \frac{Gcal}{yr} X 232 \frac{zl}{Gcal} = 1{,}095{,}000 \text{ zl/yr}$$

Average heat losses are calculated as follows, based on temperature of raw wastes 14°C:

$$HL = 0.023 \frac{Gcal}{m^3} X 300 \frac{m^3}{d} X 365 \frac{d}{yr} X 232 \frac{zl}{Gcal} = 590{,}000 \text{ zl/yr}$$

Electrical energy expenses for 100 kW installed power are calculated as:

$$EE_{exp} = 110 \text{ kW } X 24 \frac{h}{d} X 0.5 \frac{zl}{kWh} X 365 \frac{d}{yr} = 482{,}000 \text{ zl/yr}$$

Operation and maintenance costs--

The total operation and maintenance costs (OM), were calculated as:

$$OM = DC + GC - (PE - HL)$$

where direct costs (DC) were calculated as:

$$DC = (\text{material costs}) + (\text{labor costs}) + EE_{exp}$$

and general costs (GC) were calculated as:

$$GC = 0.4 \quad DC = 766{,}400 \text{ zl/yr}$$

Thus, the total OM costs are:

$$OM = 1.916 + 0.766 - (1.095 - 0.590) \cong 2.2 \ 10^6 \text{ zl/yr}$$

Economic efficiency indexes--

For System II - A-1, the E_Q index expressed per volume of wastewaters treated in a year is:

$$E_Q = \frac{41{,}500{,}000 \ (0.08 + 0.022) + 2{,}200{,}000}{300 \ . \ 365} = 58.7 \text{ zl/m}^3$$

The index expressed per COD_{nf} load removed (COD_r):

$$(14 - 0.2) \frac{kg}{m^3} X 300 \frac{m^3}{d} X 365 \frac{d}{yr} = 1{,}511{,}100 \text{ kg } COD_r\text{/yr}$$

$$E_{COD} = \frac{41{,}500{,}000 \ (0.08 + 0.022) + 2{,}200{,}000}{1{,}511{,}100} = 4.24 \text{ zl/kg } COD_r$$

TABLE 30. CAPITAL COSTS FOR SYSTEM II

Unit	Volume m^3	Unit Cost 10^3 zl/m^3	Equipment 10^6 zl	Cost - I 10^6 zl	
				A	B
Pump house	110	3.0	0.2	0.53	0.53
ANFLOW	3000	4.0	0.5; 0.65	12.50	12.65
Gas tank	2500	2.2	-	5.50	5.50
Aeration tanks	900; 1800	2.0	0.2; 0.4	2.00	4.00
Clarifiers	100	2.2	-	0.22	0.22
Thickener	300	2.8	-	0.84	0.84
Recycle pump	50	3.0	0.03	0.18	0.18
Building	600	4.0	-	2.40	2.40
Centrifuge	-	-	0.2	0.20	0.20
Sludge storage	1300; 1700 m^2	0.4	-	0.52	0.68
Landscaping	-	-	-	1.70	1.70
Piping (m)	1000	1.2	-	1.20	1.20
			SUBTOTAL	27.80	30.10
Design cost, geological survey:			15 percent	4.17	4.51
			SUBTOTAL	31.97	34.61
Unexpected purchases and labor:			20 percent	6.39	6.92
GRAND TOTAL I (10^6)				38.40	41.50
Including freezing of capital investment I' = 1.08' I (10^6)				41.50	44.80

System III

The system is similar to System II in the primary, anaerobic part of the treatment train. Following the ANFLOW reactor, the supernatant from the thickener undergoes anaerobic biofiltration in the first stage ANBIOF I^o where further biodegradation of liquified organics occurs. Thus, the gas production is more complete than in System II; it is expected that it will add at least 0.1 m^3 CH_4/kg COD_{nf} removed at L = 2 kg COD/m^3/d; i.e., some 110 m^3 biogas/d, removing at least 80 percent of the incoming COD_{nf} load. The effluent from ANBIOF I^o, containing at the most 800 mg O_2/dm^3 COD_{nf} will be fed to an aerobic biofilter with high void ratio to maintain good aeration in the first layer of the biofilter media. As found experimentally by Oleszkiewicz and Eckenfelder (175), the oriented plastic media at 100 m^2/m^3 specific surface area increases the DO level to near saturation conditions in the first 0.5 m of the filter height. The aerobic biofilter at $L \leq 0.5$ kg $COD_{nf}/m^3/d$ should yield at least 60 percent COD_{nf} removal and a well nutrified effluent with COD_{nf} of approximately 300 mg/dm^3. Anaerobic biofiltration in ANBIOF II°, judging by the results of Section 7 should yield an effluent COD_{nf} below 150 mg/dm^3. Clarification and 1 hr aeration will be applied before discharge in order to remove gaseous nitrogen and introduce oxygen to the effluent stream, yielding further removal of COD.

The primary advantages of the system are the use of easily operated biofilters, two-stage, without phase separation, though anaerobic treatment for more complete gasification, much better resistance to shocks due to high SRT in the biofilters.

System IV

The system features short detention time anaerobic digestion in the ANCONT reactors with 3.5 days HRT. Compared to System III, lower gas production is expected in the ANCONT reactor than in the ANFLOW reactor and higher in ANBIOF I° than in System III. Based on our experimental evidence, it is expected that the overall biogas production will not be much smaller in System IV. On purpose, however, low overall gas recovery value is assumed 0.25 $m^3/kg\ COD_{nf}$ introduced, 50 percent smaller than in System III in order to account, in an indirect way, for the higher level of operational difficulties with the ANCONT reactor in System IV.

The treatment efficiency of the ANCONT reactor at L = 4 kg $COD/m^3/d$ is 85 percent which compares favorably with 65 percent COD removal in ANFLOW System III at L = 1.4 kg $COD/m^3/d$. The subsequent removal train: ANBIOF I°, aerobic biofilter, ANBIOF II in System IV is designed at 10 percent lower HRT than in the System III.

It should be noted that in both treatment trains the actual performance of the ANBIOF reactor will be higher than the 73 percent COD removal attained

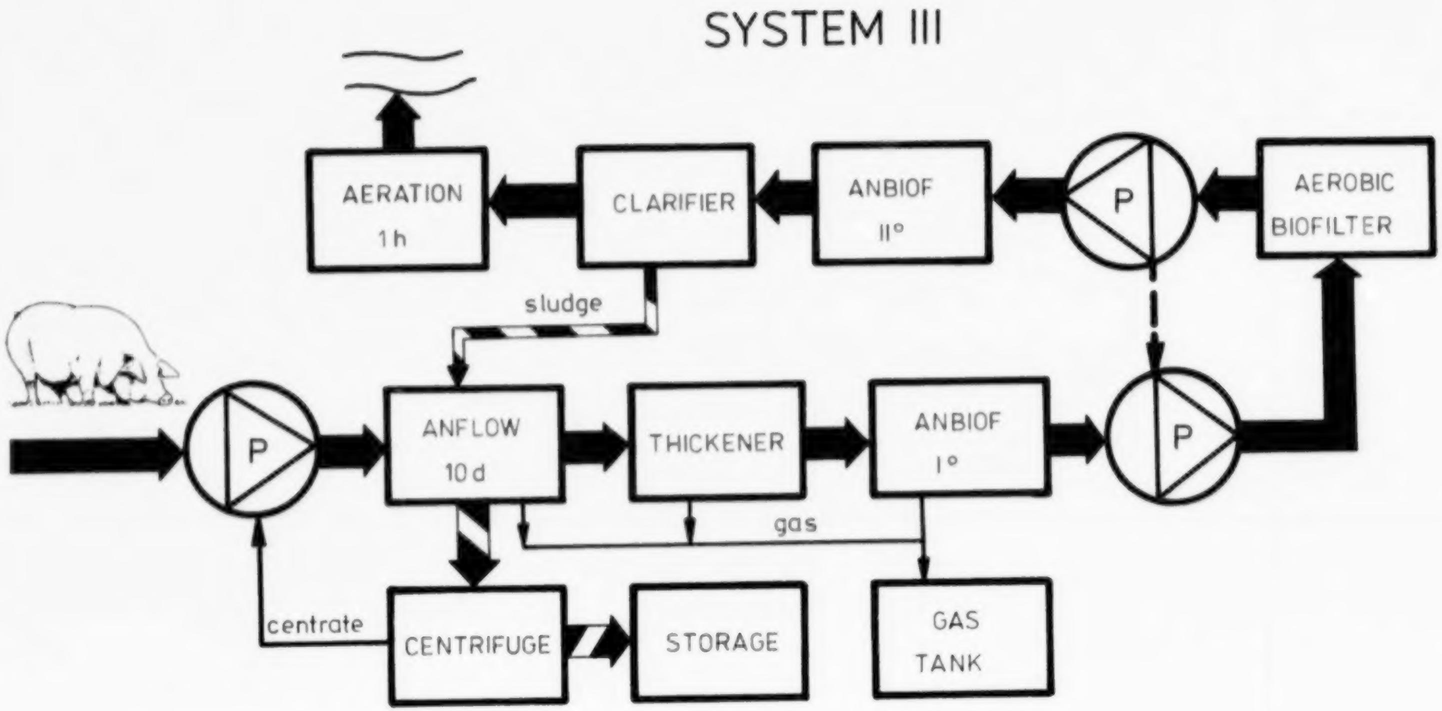

SYSTEM III
AERATION
1 h
CLARIFIER
ANBIOF
II°
P
AEROBIC
BIOFILTER
sludge
P
ANFLOW
10 d
THICKENER
ANBIOF
I°
P
gas
centrate
CENTRIFUGE
STORAGE
GAS
TANK

Figure 66. Layout of System III.

in this study at 20°C, due to higher temperature of the effluent from the thickener, designed to conserve heat and recover gas.

System V and VI

Both systems start with a settling or thickening tank with HRT = 1 day which feeds clarified wastes, through a heat exchanger to anaerobic biofilter, ANBIOF I^o where 80 percent COD_{nf} removal is assumed at $L = 3.0\ kg/m^3/d$ in both variants A and B. The actual removals that can be expected from ANBIOF I^o will be higher, as the process will be ran at 35°C, i.e. higher than the experimental data collected in approximately 20°C.

The secondary treatment in System V will be in a two-stage activated sludge system designed for approximately 25°C for I^o and 18°C for II, with the overall HRT in both stages equal to 2 days (A) and 3 days (B). In System VI the aerobic biofilter will be used with a design loading of $1.0\ kg/m^3/d$ for COD, HRT equal to 1.4 and 2.4 days followed by an ANBIOF II^o, a polishing unit with HRT = 0.67 and 1.0 days.

Both systems are treating sludge in a separate ANFLOW reactor (HRT = 15d) designed to stabilize sludge and produce gas at a maximum rate of $0.5\ m^3/kg$ COD_{nf} introduced. This arrangement separates the digestion process into two systems, the ANBIOF reactor treating low TS, low COD concentration wastewater and the ANFLOW reactor treating sludge of at least 3 to 4 percent TS and thus, results in optimum conditions for both systems. As expected, this shows in the economic efficiency indices which are the lowest for System VI.

The capital cost calculation for System VI are presented in Table 31.

Systems VII, VII-a and VII-b

These three systems compare efficiency of land disposal and agricultural utilization of effluents. Systems VII and VII-a (Figure 69) feature anaerobic pretreatment of clarified wastewaters for pathogens destruction and odor stabilization and partial carbon removal followed by three months storage, a minimum retention, if year-round, operation is to be practiced in the Polish conditions. The sludge undergoes separate anaerobic digestion, and thus, maximum gas production is effected by the system. System VII is calculated without accounting for the value of recovered N and P while VII-b includes these values.

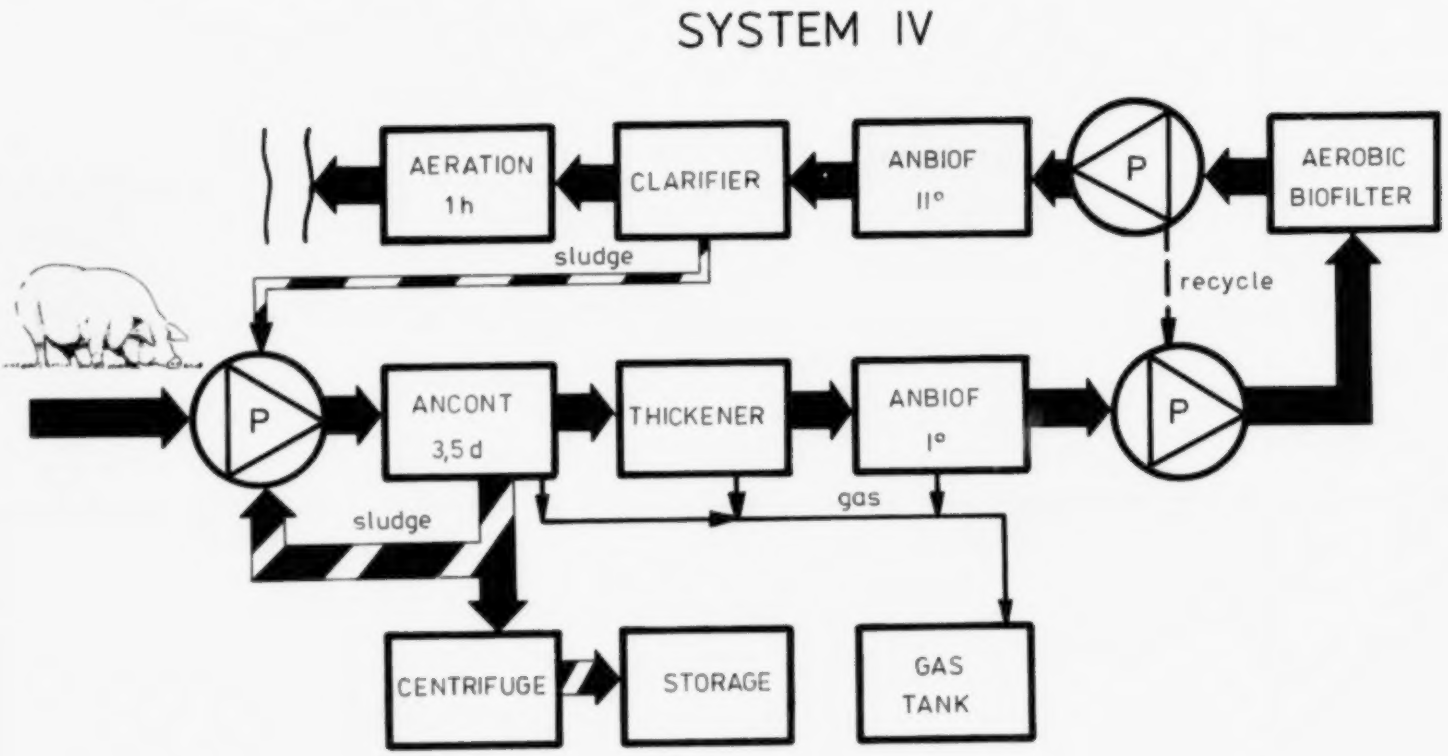

SYSTEM IV
AERATION 1h
CLARIFIER
ANBIOF II°
P
AEROBIC BIOFILTER
sludge
recycle
P
ANCONT 3,5 d
THICKENER
ANBIOF I°
P
gas
sludge
CENTRIFUGE
STORAGE
GAS TANK

Figure 67. Layout of System IV.

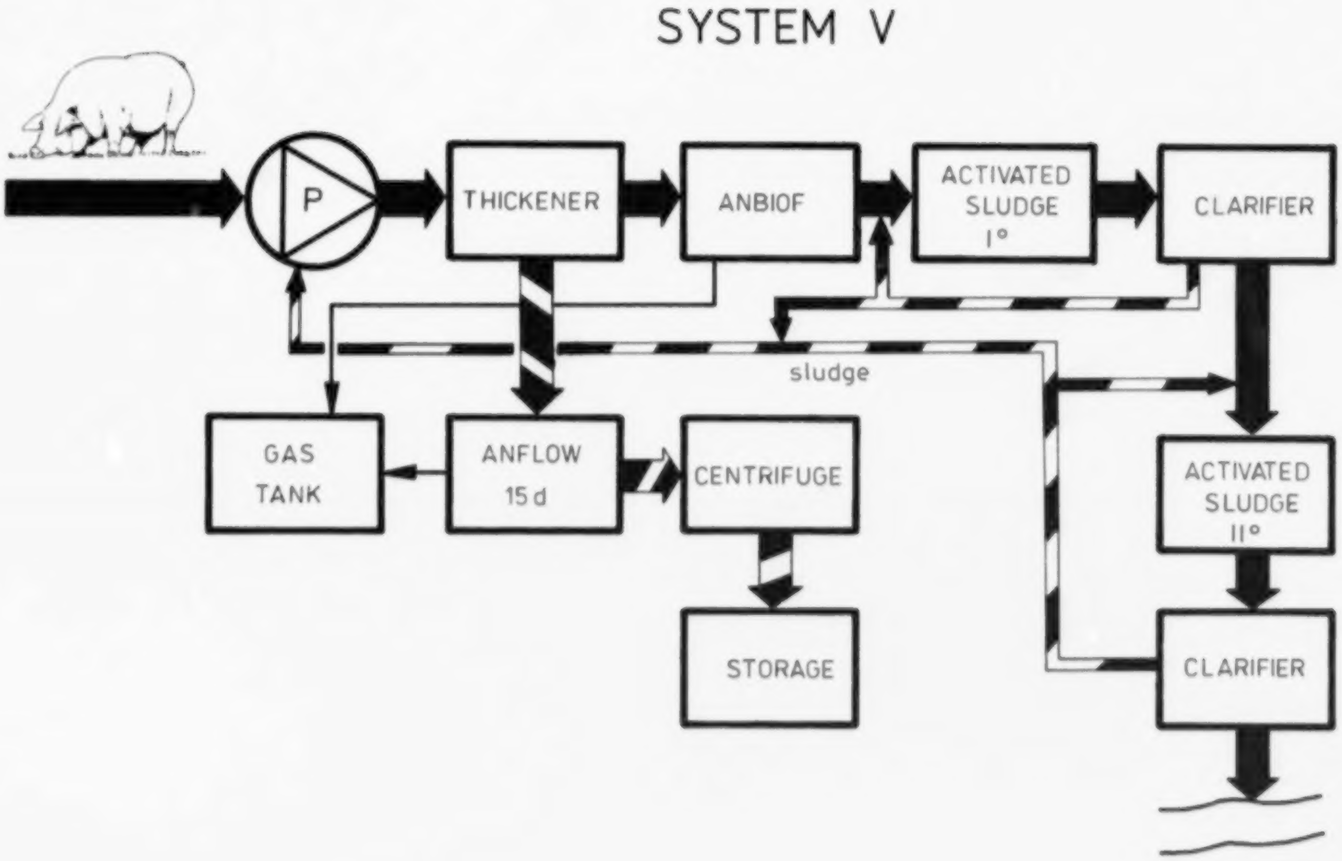

SYSTEM V
P
THICKENER
ANBIOF
ACTIVATED SLUDGE I°
CLARIFIER
sludge
GAS TANK
ANFLOW 15 d
CENTRIFUGE
STORAGE
ACTIVATED SLUDGE II°
CLARIFIER

Figure 68. Layout of System V.

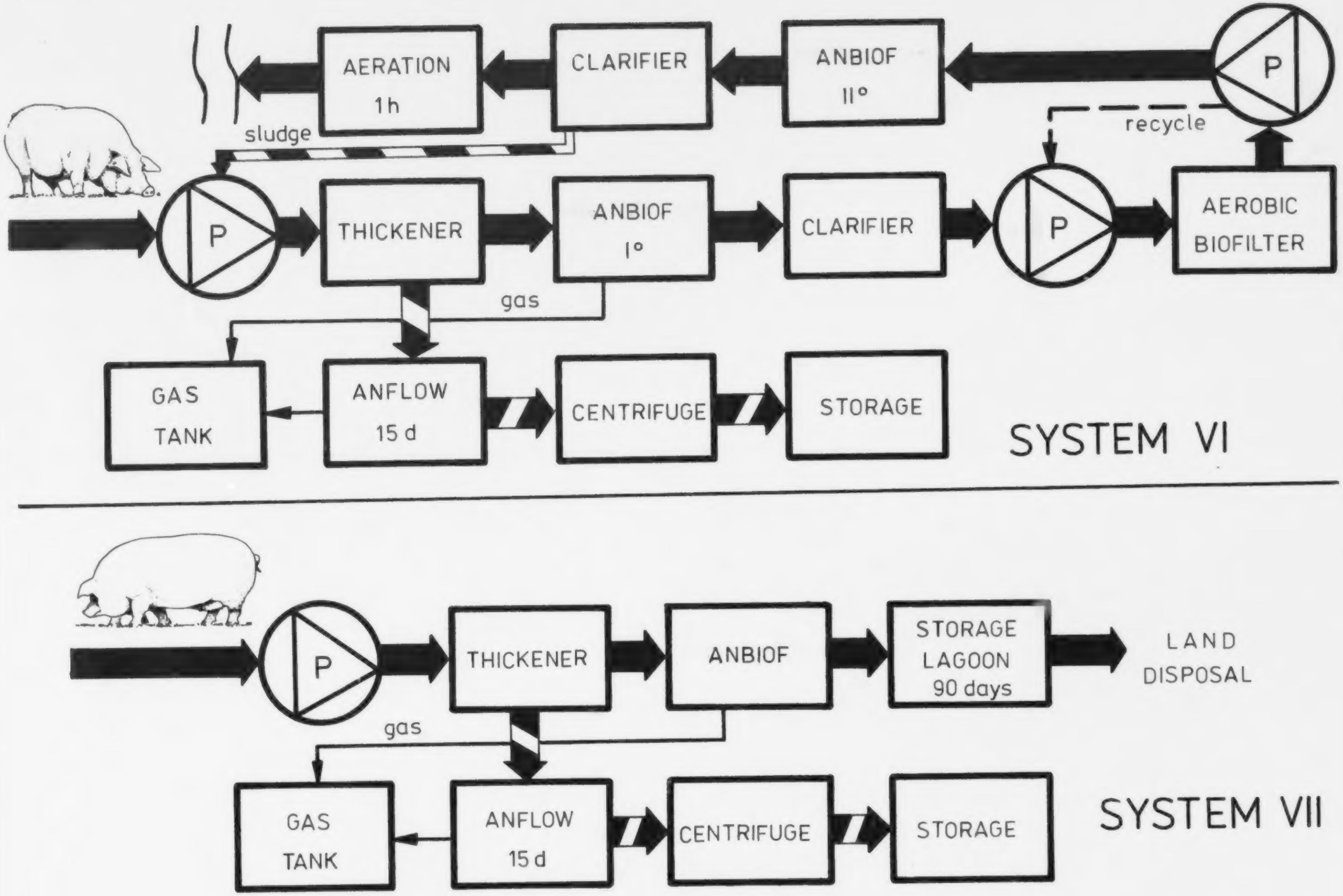

AERATION
1h
CLARIFIER
ANBIOF
II°
P
sludge
recycle
P
THICKENER
ANBIOF
I°
CLARIFIER
P
AEROBIC
BIOFILTER
gas
GAS
TANK
ANFLOW
15 d
CENTRIFUGE
STORAGE
SYSTEM VI
P
THICKENER
ANBIOF
STORAGE
LAGOON
90 days
LAND
DISPOSAL
gas
GAS
TANK
ANFLOW
15 d
CENTRIFUGE
STORAGE
SYSTEM VII

Figure 69. Layout of System VI.

TABLE 31. CAPITAL COSTS FOR SYSTEM VI

Unit	Volume (m^3) or area (m^2)	Unit Cost zl $10^3/m^3$	Equipment (10^6 zl)	Cost - I (10^6 zl) A	B
1	2	3	4	5	6
Pump house	220	3.0	0.40	1.06	1.06
Thickener	300	2.8	-	0.84	0.84
ANBIOF I^o	840; 1200	2.5	-	2.10	3.0
Clarifiers (2)	115	3.0	-	0.35	0.35
Aerobic biofilter	420; 720	2.0	-	0.84	1.44
ANBIOF II^o	200; 300	2.5	-	0.50	0.75
ANFLOW	800; 1000	4.0	-	3.20	4.00
Gas tank	800; 1000	2.2	-	1.80	2.20
Centrifuge	-	-	0.20	0.20	0.20
Sludge storage	1300; 1700	400	-	0.52	0.68
Pump-recycle	50	3.0	0.03	0.18	0.18
Building	600	4.0	-	2.40	2.40
Landscaping	-	-	-	1.70	1.70
Piping	-	-	-	1.20	1.20
		SUBTOTAL		16.88	19.99
		GRAND TOTAL (+15% + 20%)		23.50	27.60

To arrive at an adequate irrigation dose, we have compared the data quoted by Loehr (13) 26 g TKN/hod/d; by Overcash and Humenik (168) 0.230 kg N/450 kg LW/d and 0.068 kg P/450 kg LW/d; with our own data reported in Section 4, and have assumed: 30 g N/head/d and 9.3 g P/head/d for this analysis.

The agricultural utilization was calculated based on Majdowski's elaborate lysometric studies on piggery wastes (166) conducted from the standpoint of effluent quality. From his long-term studies, conducted at various concentrations and doses, a 25 mm dose (250 m^3/ha/yr) was selected since at S_o = 4000 mg/dm^3 of BOD_5, it yields an effluent (drainage) of 1.4 to 45 mg O_2/dm^3 of BOD_5. Thus, an area of 430 ha for both Plants A and B is assumed, which at 53,000 zl/ha for a spray irrigation system (167) yields capital costs of 22.8 X 10^6 zl for the land disposal alone and an overall cost of 71.8 X 10^6 zl. In practice this area could be doubled increasing the costs, since the recent

USDA manual (165) recommends that only half of the nitrogen dose be applied as manure and the other half as artificial fertilizer in order to control phosphorus runoff because there is an excess of phosphorus in piggery wastes.

System VII-b features land disposal only after 90 days retention in a holding lagoon and no other pretreatment. The costs are significantly reduced when compared with VII and VII-a, however, are still much higher than the costs of other treatment systems for disposal. This illustrates the reasons why designers are becoming discouraged with large piggery farms: the economics of land disposal were against this form of wastes disposal; the artificial treatment trains as used so far were offering no better alternatives.

System VIII

This is the reference Vidus-type treatment system which has been made comparable with Systems I through VI, and is calculated to bring comparable effluent quality. The activated sludge is designed as a one-stage process at HRT (A) = 3 d, and HRT (B) = 4.5 d and ANBIOF II^{o} HRT (A) = 1 d, and and HRT (B) = 1.5 d. Full sludge stabilization is applied to bring sludge to quality comparable with other systems.

Discussion

Table 32 lists the economic efficiency indices for all systems studied. Systems V and VI are found to be the least expensive. It is characteristic that the so-called "natural" treatment systems I and VII, VII-a and VII-b are more expensive than some of the new stream disposal systems. This means that further wastewater volume reduction is necessary in order for the land disposal systems to become economically efficient as the costs of fertilizers are still low (VII-a and VII-b). Anaerobic digestion is the preferred method of pretreatment in all systems, including VII due to: energy recovery, 90 + percent nitrogen conservation and pathogen stabilization.

It is noted that increased power costs beyond 1.50 zl/kWh, in the near future will make systems with gas recovery even more attractive provided that the ANCONT- or ANBIOF-type reactors are used.

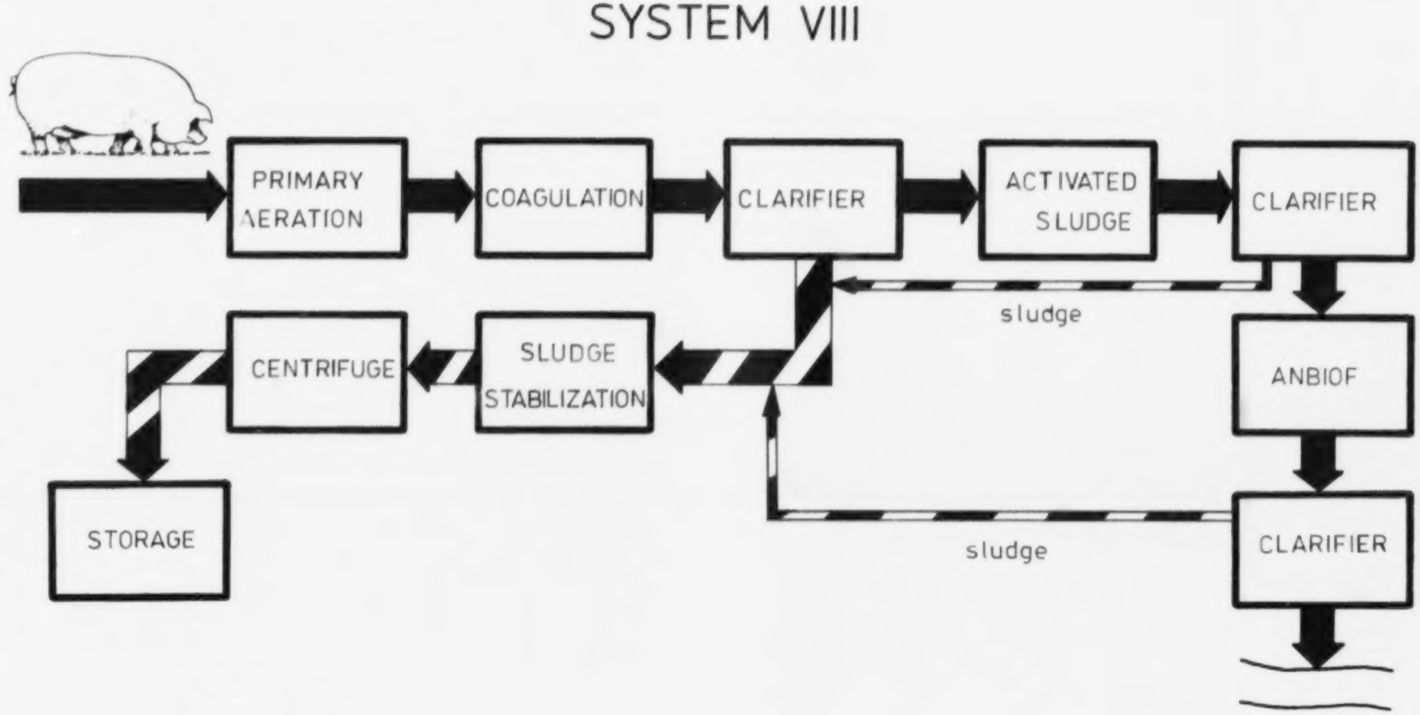

SYSTEM VIII
PRIMARY AERATION
COAGULATION
CLARIFIER
ACTIVATED SLUDGE
CLARIFIER
sludge
ANBIOF
CLARIFIER
sludge
SLUDGE STABILIZATION
CENTRIFUGE
STORAGE

Figure 70. Layout of System VII and VIII.

TABLE 32. ECONOMIC EFFICIENCY INDICES FOR THE STUDIED PIGGERY WASTEWATER TREATMENT SYSTEMS

System	Variant	Power Cost Level	Recovered Gas	Capital Costs-1	Recovery Power + Heat PE	Power Consumption EE_{exp}	Efficiency E_Q	Efficiency E_{COD}	Notes
			$10^3 m^3$	10^6 zl	10^6 zl/yr		zl/m^3	zl/kg	
1	2	3	4	5	6	7	8	9	10
I	A	1 2		30	n.a. n.a.	0.45 1.30	43.9 54.8	3.2 4.0	PONDS
	B	1 2		36	n.a. n.a.	0.60 1.70	52.6 67.3	2.7 3.4	
II	A	1 2	1.8	38.4	1.10 2.80	0.50 1.45	53.7 61.5	4.2 4.4	ANFLOW
	B	1 2	2.4	41.5	1.45 3.70	0.50 1.45	59.3 56.5	3.0 2.9	
III	A	1 2	2.2	40.0	1.35 3.45	0.20 0.50	53.9 45.7	3.9 3.3	ANFLOW
	B	1 2	3.0	42.0	1.80 4.65	0.20 0.50	52.2 36.7	2.6 1.8	
IV	A	1 2	1.1	24.5	0.70 1.75	0.20 0.50	40.6 41.1	3.0 3.0	ANCONT
	B	1 2	1.5	27.0	0.90 2.35	0.20 0.50	40.7 33.0	2.0 1.9	
V	A	1 2	2.2	22.7	1.30 3.25	0.50 1.45	39.1 30.2	2.8 2.8	ANBIOF and activated sludge
	B	1 2	3.0	27.0	1.80 3.30	0.50 1.45	35.9 31.2	2.0 1.5	
VI	A	1 2	2.2	23.5	1.35 3.45	0.20 0.50	35.5 35.5	2.6 2.5	ANBIOF and activated sludge
	B	1 2	3.0	27.6	1.80 4.65	0.20 0.50	36.0 20.4	1.8 1.0	
VII	A	1 2	1.8	71.8	1.10 2.80	0.20 0.50	98.7 93.2	7.1 6.7	Without N and P bonus
	B	1 2	2.4	75.1	1.45 3.75	0.20 0.50	100.2 90.1	5.1 4.5	
VII-a	A	1 2	1.8	71.8	1.10 2.80	0.20 0.50	85.0 79.5	6.1 5.8	N and P bonus
	B	1 2	2.4	75.1	1.45 3.75	0.20 0.50	80.6 70.1	4.1 3.5	

Continued

Table 32 Continued

System	Variant	Power Cost Level	Recovered Gas	Capital Costs-1	Recovery Power + Heat PE	Power Consumption EE_{exp}	Efficiency E_c	Efficiency E_{COD}	Notes
			$10^3 m^3$	10^6 zl	10^6 zl/yr		zl/m^3	zl/kg	
1	2	3	4	5	6	7	8	9	10
VII-b	A	1		58.5	n.a.	0.20	67.1	4.8	N and P bonus
		2			n.a.	0.50	70.3	5.1	
	B	1		59.6	n.a.	0.20	64.6	3.3	
		2			n.a.	0.50	68.0	3.4	
VIII	A	1		19.2	n.a.	0.55	47.6	3.4	Modified Vidus system
		2			n.a.	1.70	62.2	4.5	
	B	1		22.2	n.a.	0.55	50.7	2.6	
		2			n.a.	1.70	65.3	3.2	

NOTE: Heat loss is 1) 0.59 10^6; and 2) 1.26 10^6 zl/r, both variants. Costs for VII-VII-b do not include land (430 ha) and power for irrigation by spraying.
1 U.S. $ is equivalent to 20 zl.

The secondary treatment systems utilizing activated sludge are very costly because of high power consumption, difficult to operate and should not be included in the piggery wastes treatment plants.

System's I principal advantages are low level of sophistication in construction and in operation, resistance to shocks and power failures (gravity flow). All these factors are very important in rural conditions. The disadvantages are lack of recovery incentive and power costs.

System II features perhaps the most complicated operation and treatment process vulnerable to shocks, however, offers an advantage of combining wastewater and sludge treatment in one train.

System III offers similar advantages to System II, and a much simpler operation of the secondary system, larger specific biogas production and high-rate low-volume secondary treatment in an aerobic biofilter and an anaerobic polishing biofilter.

System IV offers much small volume of the anaerobic digester and higher removal efficiency than System III, thus, a more stable operation of the subsequent treatment units.

Systems V and VI offer separate sludge digestion and the easiest to operate waste treatment trains. The arrangement (patent applied for by authors) now implemented at Farm A allows for rapid removal of soluble pollutants in a series of biofilters with biogas bonus and significant denitrification in ANBIOF II^o and through recycle of aerobic biofilter effluent to the ANBIOF I^o. The costs of the two Systems V and VI are the lowest of all systems compared. The beneficial effects of increased concentration of wastes and biogas recovery are apparent at the high electricity cost level which for System VI B-2: 20.4 zl/m^3 and 1.0 zl/kg COD$_{rem}$ as compared to A-2 (high-cost low-concentration) 35.3 zl/m^3 and 2.5 zl/kg COD$_{rem}$ (Table 32). These indices are in great contrast with the Vidus-type plant (VIII) which for E-2 are 65.3 zl/m^3, and 3.3 zl/kg COD$_{rem}$, and for A-2 are 62.2 zl/m^3 and 4.5 zl/kg COD$_{rem}$.

Finally, it should be noted that the presently used aerobic systems, like System VIII and the land disposal Systems VII-a and VII-b, here calculated with underestimated power costs, will show an increase in the index values due to increasing power costs while gas recovery Systems II through VI will improve the economic indices since the rising power costs usually decrease their value. The use of the System VI makes the plant independent of the fluctuation of volume of wastewaters since biofilters are less vulnerable to hydraulic overloading than suspended sludge reactors.

COMBINED TREATMENT WITH OTHER EFFLUENTS

Large piggeries are frequently sited close to large municipalities and within industrial complexes or areas otherwise unfit for land disposal. Three possible solutions to combined treatment of animal wastes result from these studies presented here so far:

a. feed yeasts production with the use of piggery wastes and combined wastes treatment;

b. combined anaerobic digestion with municipal sludge for biogas recovery; and

c. combined treatment with nutrient deficient industrial wastes.

Yeast Production

The studies of Candida yeasts production on piggery wastes with and without the addition of easily available carbon have proved much higher nutrients (C, N, and P) utilization in the runs with carbon supplementation. Technical feasibility of yeast production was verified in semidynamic tests, however, it should be noted that at present the high costs of molasses and unusually low costs of yeasts make the concept economical only when the two plants are within one industrial complex, and when there is the benefit of joint management of recovered gas and waste heat. In the conceptual layout in Figure 71 piggery wastes are clarified, and the sludge is thickened or centrifuge is an alternative and fed to the combined mesophyllic anaerobic digestor operating as an ANFLOW reactor. The raw supernatant or centrate is directed to the yeast plant as N and P rich substrate, carbon is fed as 6600 kg/d of molasses for yeast production. Effluent (centrate) from yeast production is fed to the ANFLOW for gas generation and stabilization. The ANFLOW effluent is subject

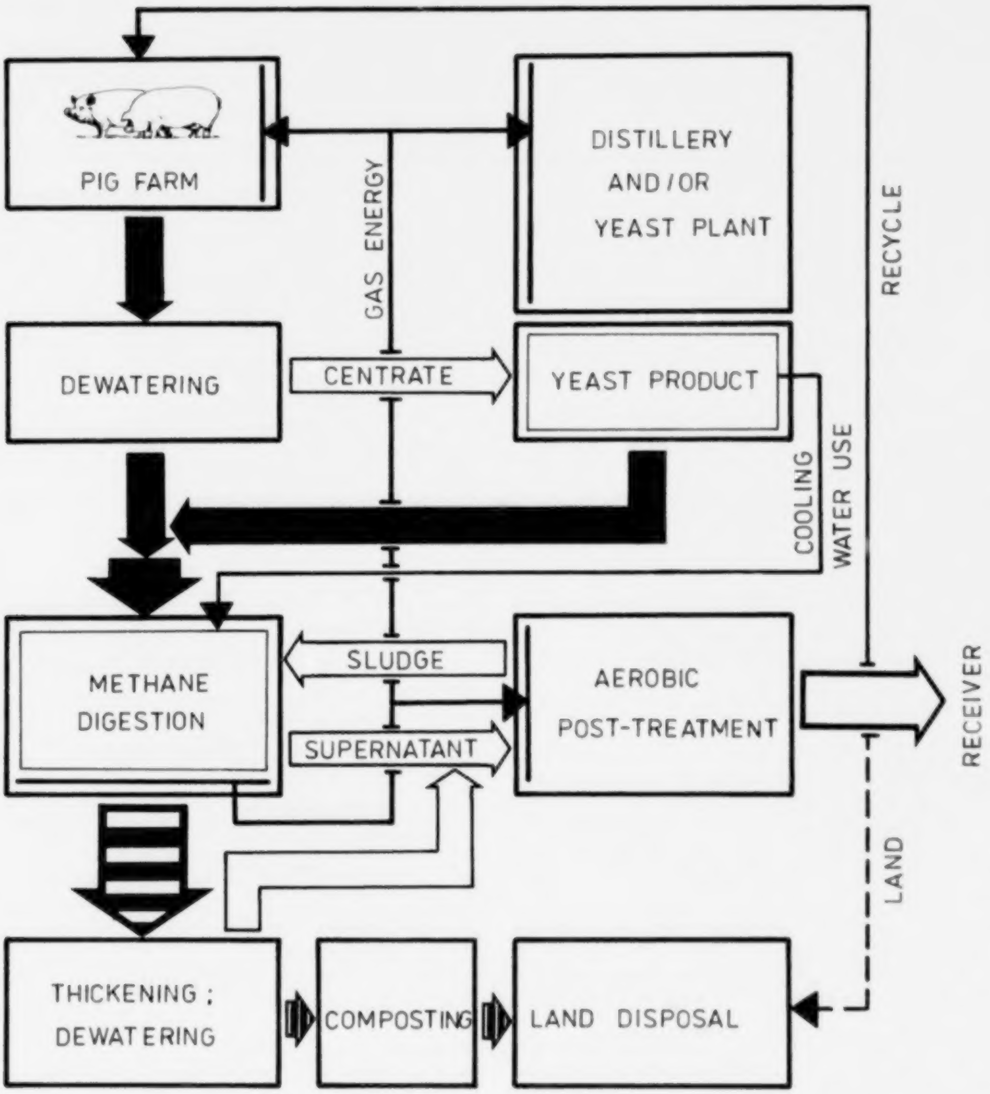

PIG FARM
DISTILLERY AND/OR YEAST PLANT
GAS ENERGY
RECYCLE
DEWATERING
CENTRATE
YEAST PRODUCT
COOLING WATER USE
METHANE DIGESTION
SLUDGE
SUPERNATANT
AEROBIC POST-TREATMENT
RECEIVER
LAND
THICKENING; DEWATERING
COMPOSTING
LAND DISPOSAL

Figure 71. Layout of combined wastes management - recycle system for pig farm and yeast plant.

to separation into liquid phase which undergoes further treatment, while the solid phase after dewatering and composting is used in agriculture.

Recycle of treated wastewaters for pig farm use and recycle of waste heat from the yeast plant, as well as full utilization of all carbonaceous matter generated at both plants into methane generation increase the economic feasibility of this joint venture.

The efficiency indices are calculated based on 300 m^3/d piggery wastes flow for variant A-1 assuming System V, Figure 68 and Table 33. The fodder yeast plant is calculated as using and discharging 300 m^3/d of water. In a combined plant where raw wastes are fed, an effluent will be 400 m^3/d. The values of $E_Q = 34.7$ zl/m^3 and 2.5 zl/kg $COD_{removed}$, a considerable difference from the separate plants when the fact of decreased volume of wastes is taken into account. Thus, although the use of yeast production as a method of piggery wastes treatment is still uneconomical, in a combined production, waste treatment, recovery system the economics are in favor of combined pig wastes fermentation. The benefits are:

a. decreased use of water by 50 percent and decreased volume of wastewaters;
b. treatment of very concentrated and difficult to treat aerobically effluents from yeast plants;
c. higher treatment efficiency due to better C/P/N ratio in yeast wastes;
d. rational use of waste heat from yeast plant;
e. better use of nutrients in pig wastes and higher carbon removal than in case of separate treatment systems; and
f. increased energy recovery and decreased investment, operation and maintenance costs.

As found in this work, anaerobic processes are the best for both full treatment and pretreatment before agricultural wastes disposal. This is utilized here as shown in Figure 72. Municipal sewage is transported by gravity or pumped to the combined treatment plant (CTP) located 2 to 5 km from the town. At the CTP sewage undergoes screening, grit removal, primary

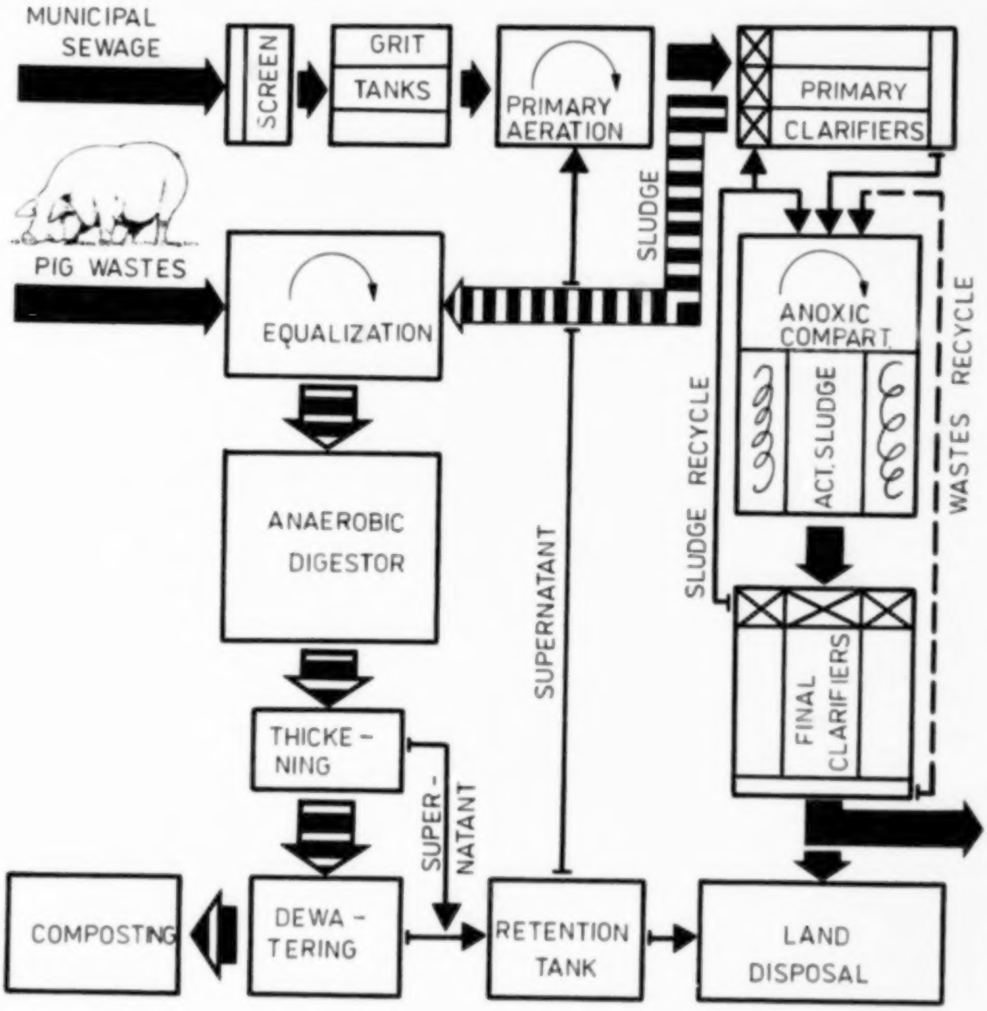
TABLE 33. COST OPTIMIZATION FOR THREE COMBINED TREATMENT PLANTS

W.T. Plant		Capital Costs	O - M Costs	Recovery EE, HE	Power Use	Net Profit	Economic Efficiency Indices	
							E_Q	E_{COD}
Type	Flow m^3/d			10^6 zl/yr			zl/m^3	zl/kg COD
Piggery WTP (System V)	300	23	2.5	1.3	0.5	0.7	39.3	2.8
Yeast fact. W.T.P.	300	23	2.5	1.3	0.5	0.7	39.3	2.8
Combined W.T.P.	400	29	3.1*	2.0	0.57	1.22	34.7	2.5
Piggery WTP	300	23	2.5	1.3	0.5	0.7	39.3	2.8
Municipal WTP	2,500	50	4.5	0.5	0.87	0.03	11.0	16.3
Combined WTP	2,800	67	5.0	0.43	0.88	0.45	11.8	2.2
Piggery WTP (System VIII)	300	20	3.1	-	0.55	-	47.6	3.4
Chemical factory WTP	25,000	210	10.0	-	5.7	-	3.4	4.8
Combined WTP	25,300	230	10.0	0.3**	5.7	-	3.6	4.0

*Profit from N and P recovered in yeast biomass (1.5 million zl) not included.

**Phosphorus recovery included only 90 kg P/d 0.3 mln zl/yr.

1 Dollar is equivalent to 20 zl



MUNICIPAL SEWAGE
SCREEN
GRIT
TANKS
PRIMARY AERATION
PRIMARY
CLARIFIERS
SLUDGE
PIG WASTES
EQUALIZATION
ANOXIC COMPART.
ACT. SLUDGE
SLUDGE RECYCLE
WASTES RECYCLE
ANAEROBIC DIGESTOR
SUPERNATANT
FINAL CLARIFIERS
THICKE - NING
SUPER - NATANT
COMPOSTING
DEWA - TERING
RETENTION TANK
LAND DISPOSAL

Figure 72. Concept of combined municipal - piggery wastes treatment system.

aeration, settling, activated sludge treatment and final clarification. The primary and excess activated sludges are mixed with piggery wastes and fed to the anaerobic flow-through digester (ANFLOW) operated conventionally for maximum biogas recovery (HRT = 10 days). Effluent from ANFLOW is thickened and dewatered for composting while supernatant is directed to an equalization tank for agricultural disposal or to the aerobic treatment train. In the latter situations the aeration tank has to be preceded by an anoxic compartment to account for excessive concentrations of nitrogen in wastes stream. Anoxic zone is equipped with mixers for contacting incoming wastes with carbon-deficient recycled sludge.

The economic comparison for CTP serving 15,000 inhabitants (2,500 m^3/d) and a farm with 10,500 hogs (300 m^3/d) is presented in Table 33.

The capital costs may be further diminished by substituting the ANCONT in place of the ANFLOW digester although maintenance costs may go up and biogas recovery will be less efficient.

The combined municipal pig wastes systems are recommended for wider use in Czechoslovakia (152, 157). The city of Trebon (30,000 population equivalents) and a 25,000 hog farm have erected a CTP which, in an initial phase of operation, has attained 3 m^3 CH_4/kg TS/d producing some 4000 m^3/d of biogas at 67 percent methane. With the foreseen increase of pig farm to 60,000 head capacity, the plant operators expect to attain 0.150 m^3/hog/d of biogas and the aeration power input 2W/hog.

It should be noted that high content of nitrogen in the supernatant poses serious problems. A system as proposed here in Figure 72 with an anoxic sludge compartment offers a solution, however, adequately large capacity and skillful maintenance is required. A conventional activated sludge system, as used in Trebon (152) will not remove nitrogen to the degree allowing for stream disposal, since the supernatant may contain 10 to 15 g/dm^3 TS, 3 g/dm^3 TKN and up to 5 g/dm^3 $BOD_{5,nf}$.

Combined Treatment with Industrial Wastes

A combined treatment plant in Czechoslovakia treats 120 m^3/d of pig waste with 60,000 m^3/d of kraft pulp effluents (152). In another case, analyzed in this project, an organic chemicals plant treats it wastes with activated sludge. The performance of aeration basin, without addition of nutrients, was some 30 percent, thus, the chemical plant has to spend close to 0.9 10^6 zl/year on artificial fertilizer in the first stage (25,000 m^3/d) and some 1.7 10^6 zl/year in the second stage (75,000 m^3/d).

Similar systems are designed by authors at a 24,000 head capacity Agrokomplex farm which produces 600 to 800 m^3/d of wastes, twice the existing Vidus plant hydraulic capacity. In order to accomodate these wastes a pressure (150 mm ID) pipe was designed to pump the excess 300 m^3/d of screened, pre-aerated piggery wastes to a chemical plant located 11 km away (see Figure 73).

The chemical plant nutrient demand: 320 kg N/d and 90 kg P/d (I stage) will be adequately covered by raw pig wastes. The analysis in Table 33 does not include savings due to lower costs of equipment feeding nutrients ready to the aeration tank and includes only the cost of phosphorus.

The benefits are apparent and show an excellent route for the use of animal wastes as natural nutrients in waste treatment of unbalanced industrial wastes.

CONCLUSIONS

The so-called "natural" treatment systems featuring lagoons, oxidation ponds earthen structures and agricultural utilization (land disposal), Systems I and VII-b, have been proved less economical for the modern large scale industrial pig farm, which use water in excess of 20 dm^3/hog/d, than the new systems proposed in this project utilizing full biogas recovery and anaerobic treatment, Systems V and VI.

Systems I and VII-b are, however, still more economical than the presently used chemical-biological systems (System VIII) and some of the anaerobic treatment systems now proposed by various sources.

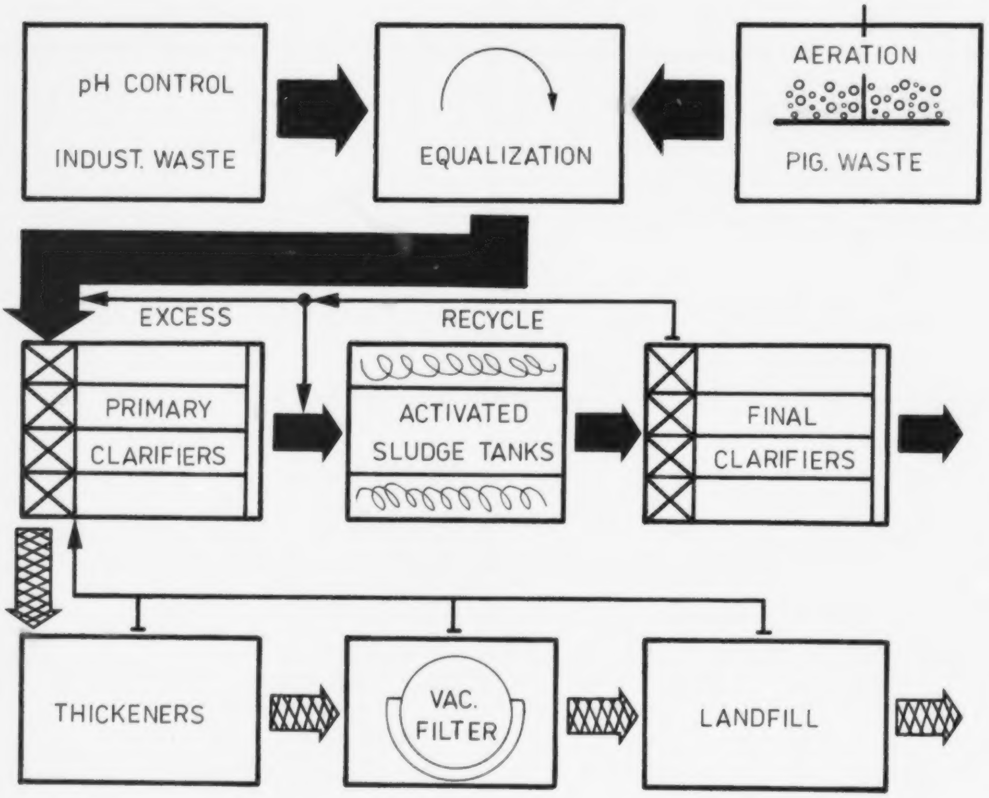

pH CONTROL
INDUST. WASTE
EQUALIZATION
AERATION
PIG. WASTE
EXCESS
RECYCLE
PRIMARY
CLARIFIERS
ACTIVATED
SLUDGE TANKS
FINAL
CLARIFIERS
THICKENERS
VAC.
FILTER
LANDFILL

Figure 73. Concept of combined treatment with chemical industry wastes.

The high concentration of nutrients in piggery wastes makes these effluents ideal substrate for combined treatment with high-volume low-concentration, nutrient deficient industrial wastes.

Location of pig farms close to municipalities creates an opportunity of combining the separated solids from municipal sewage with pig wastes for a more efficient biogas recovery operation.

The location of pig farms within the complexes of other agricultural industry segments creates an opportunity to combine other concentrated effluents for gas recovery, waste heat utilization operations in ANFLOW or ANCONT type digesters.

Analyzing the trends in neighboring countries with similar animal wastes problems (152) and the recent recommendation in Poland (158), as well as the results of this economic analysis, it is conluded that the pig farms should have a capacity much lower than 10,000 head if agricultural utilization is to be practiced. If larger farms are erected or in cases where land disposal is not feasible, the piggery wastes should be treated in combination with other industrial effluents or municipal sewage. Due to increased size of the combined waste treatment facilities and significant generation of marketable products, biogas and digested sludge or compost, better quality of operation can be maintained than in local plants. The decrease in capital costs is usually significant (e.g. 20 to 25 percent) in spite of frequent need for transporting the wastes to the CTP site. The decrease in running costs, even without accounting for the recovered biogas, for the joint treatment facilities may be as large as 20 to 50 percent of the sum of these costs at individual plants.

In all cases advanced biogas recovery high-rate treatment systems should be applied, such as the ANBIOF I^{o} AEROBIC BIOFILTER - ANBIOF II^{o} System VI, which are more efficient technologically and economically than the presently used treatment systems and will become the only alternative with the increasing energy shortage.

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